Review article

How generalisable are material extrusion additive manufacturing parameter optimisation studies? A systematic review

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HIGHLIGHTS

- Studies investigating ME AM part quality show no consistency in methods and results.
- Prior work is not widely generalisable; each study has a specific experimental set-up.
- Nozzle-gap-height, print-head-speed & filament-volumetric-speed are key parameters.
- There is a lack of agreement about how to optimise key parameters.
- Single strand behaviour and underlying mechanisms of part quality need further study.

ARTICLE INFO

Keywords:
Material extrusion additive manufacturing
Fused deposition modelling
Filament behaviour
Printing parameters
Dimensional accuracy
Review

ABSTRACT

Goal: Material extrusion additive manufacturing, is a relatively inexpensive and popular manufacturing technique that can be used to fabricate complex 3D geometries at low cost. However, parts produced by this process are often characterised by poor quality, particularly with regards to dimensional and geometrical accuracy. This review provides a comprehensive analysis of experimental studies conducted over the past 25 years that have aimed to improve these quality variables via printing parameter optimisation.

Methods: An initial non systematic scoping study coupled with a subsequent scientific systematic literature review protocol to identify experimental studies on dimensional quality in material extrusion additive manufacturing was conducted. 127 individual studies are identified and analysed.

Results: The authors critically analysed the relevant and salient studies (127) by evaluating which machines; materials; sample sizes; artefact designs; and most importantly what printing parameters have been used in the experimental investigations. A total of (79) machine variations were used; ABS and PLA made up (43%) and (36%) of materials investigated respectively; (84%) of studies had sample sizes of less than (40); and artefact dimensions ranged from (10–270 mm) (1–240 mm), and (3.5–220 mm) in the X, Y, and Z axes respectively. In many cases, the relationships between printing parameters (independent variables) and dimensional qualities (dependent variables) were found to be uncertain or even contradictory between studies.

Conclusions: A wide range of studies have sought to optimise parameters (e.g., Nozzle gap height, print head velocity, filament volumetric velocity) to address dimensional quality issues in ME AM. However, the authors have demonstrated that a lack of agreement among studies limits the generalisability of these parameter optimisation findings. More recent studies have considered the local dimensional variance of deposited single strands. This offers greater potential to understand the underlying causes of component defects and inaccuracy.

1. Introduction

Material Extrusion Additive Manufacturing (ME AM) also known as fused deposition modelling (FDM), fused filament fabrication (FFF), and fused layer modelling (FLM) is one of the most popular AM techniques, especially amongst non industrial users [1]. ME AM is regarded as inexpensive in comparison to alternative AM techniques, whereby printers can cost as little as USD150. Due to the proliferation of this low cost technology, it is estimated, that by 2027, the ME AM market of “non hobbyist and consumer” users will generate USD2.2B in printer and hardware sales [2].
Figure 1 depicts an illustrative schematic of the ME AM extrusion process and its components.

ME AM is seen as an attractive alternative to many conventional manufacturing technologies because of a number of intrinsic and well documented advantages: convenience, versatility, multi material parts, and reduced time to market. Moreover, it is a comparatively low cost way to produce parts in small volumes and for prototypes due to cheaper hardware and raw materials [3, 4]. However, there are also some significant limitations that prevent ME AM being adopted as a primary production process. The process is also considered to have some mechanical performance limitations, especially anisotropic strength, and stiffness with poor performance in the build direction. ME AM is significantly slower than that of conventional mass manufacturing techniques such as injection moulding [5].

One of the most significant limitations that inhibits uptake for production quality components relates to the achievement of dimensional accuracy, surface finish, and geometrical accuracy [6, 7]. Poor DQ is one of the most commonly referenced limitations and substantial efforts are being undertaken in addressing it [8]. ME AM parts need to meet the requirements that they have been engineered for, if they don’t fit together or exhibit defects i.e., poor DQ, they will not be functionally purposeful. ME AM parts should match the nominal dimensions set prior to manufacturing. Attempts to improve component build time by optimising parameters such as increasing the layer height or increasing print speed, often have a detrimental impact on dimensional accuracy (DA).

Recognising the importance of improved DQ as ME AM continues to develop; this review article focuses exclusively on examining literature relating to DQ. Of the DQ limitations, poor DA is especially regarded as a significant boundary for full acceptance [9, 10]. For example, one study reported that ME AM fabrication has a failure rate of 41.1%, whereby ~25% of total failures were due to poor DQ as a consequence of processing difficulties [11]. It is widely acknowledged throughout existing literature that dimensional quality errors are significantly influenced via printing parameter selection [12, 13, 14].

Whilst it is recognised that ME AM suffers from poor DQ, there are multiple methods of addressing this issue. It should first be noted that there is a distinction to be made between studies which solely characterise the current performance of the process ‘error analysis’ and those which aim to make improvements in some way (‘error improvement’) [15]. Amongst error improvement studies, a further categorisation can be made; ‘error avoidance’, ‘error compensation’ [16] and post processing. This review focuses specifically on parameter optimisation studies, a major area of research within error avoidance.

Currently, although many studies have been undertaken there is no clear consensus on which printing parameters have the greatest effect on DQ, what the optimal values of these are and what the magnitude and nature of the remaining errors are when optimisations are made. This review aims to benefit a wide audience. Commercial interests, researchers and hobbyists can all use its findings to gain insights in the state of the art research being undertaken in improving the ME AM process. We also hope that this review is of use to academics in this domain to help focus and steer future work in a beneficial direction. Thus, in this review:

- The authors demonstrate a comprehensive analysis of the state of the art experimental studies that have made efforts in elucidating poor DQ as a function of printing parameter modulation.
- The authors provide a detailed synthesis on how DQ is significantly influenced by an increase and/or decrease in certain printing parameter values.
- The authors critically examine the landmark studies that are exploring novel approaches to understanding and enhancing DQ and precision of ME AM produced parts.
- The authors discuss the complexities in optimising printing parameters for improving the DQ of printed parts and the scope for future work.

2. Literature search methods

2.1. Literature review search strategy

In order to critically analyse extant literature which examines the DQ of printed parts, a rigorous systematic literature review was completed. To ensure that all relevant studies were identified, two review approaches were undertaken. Initially, a non systematic scoping study also known as a mapping review was used. A scoping study is defined as a review of a body of literature that can be of particular use when the topic has not yet been extensively reviewed [17]. This was performed to assess the subject area in general and to determine key areas requiring further investigation. This provided an initial foundation for this review. This initial non systematic scoping study identified which printing parameters have previously been investigated and shown to influence the DQ, and therefore informed keywords and synonyms for the second review approach.

2.2. Systematic literature review protocol

Systematic reviews aim to identify, evaluate, and summarize the findings of all relevant individual studies within a specific subject area, thereby making the available evidence more accessible to the wider community in order to make informed future decisions [18]. A rigorous systematic literature review protocol was conducted using a targeted search strategy by employing the Scopus search database. Scopus has been the largest abstract and citation database of peer-reviewed literature, which includes scientific journals, books, and conference proceedings. Thus, due to this extensive database, Scopus was chosen as the search engine for this systematic literature review protocol. This review coupled search terms (“Material Extrusion Additive Manufacturing”, “ME AM”, “Fused
Deposition Modelling”, “FDM”, “Fused Filament Fabrication”, “FFF”, “Fused Layer Modelling”, “FLM”, “3D Printing”, “Rapid Prototyping”) with key words (“Dimensional Accuracy”, “Geometrical Accuracy”, “Part Quality”, “Dimensional Variation”, “Dimensional Tolerance”) through the use of the Boolean operator (AND); e.g. “Rapid Prototyping” AND “Part Quality”. The search terms defined the AM technology and its termed synonyms, whereas the key words specified the area of interest. Initially, each new search term was input excluding key words, e.g., termed synonyms, whereas the key words specified systematically. The resultant documents were identified by searching for the input search term in article titles, abstracts, and keywords specifically. In order to filter the results, and identify the salient documents, the search strategy explicitly targeted articles, conference papers, and reviews. The results were subsequently reviewed by reading the documents in full. During the filtering down process, 4837 studies were rejected. Studies were rejected for being non experimental, explicitly comparing desktop machines, comparing materials, investigating mechanical properties of parts, examining surface roughness and not DA, and validating numerical models. Furthermore, if a study had already been identified in a previous search, this duplication was also rejected and not included again in the final sample.

2.3. Literature review methodology and results

For the initial scoping study, 123 studies were identified. Subsequently, 5063 documents were identified by employing the Scopus review protocol. Out of the 5063 studies, 226 were determined to be of relevance. A combined total of 349 studies were therefore identified as shown in the review methodology in Figure 2. The methodology in Figure 2, illustrates the procedure used to identify the studies that were of importance and would be critically analysed in this review article.

During the review phase, additional studies were discovered using the reference lists from the reviewed studies, in a process referred to as ‘snowballing’. This identified 31 further studies which were subsequently included in the review phase. 197 studies were discarded upon further analysis as either irrelevant (i.e., studies that were not explicitly investigating process optimisation) or for being descriptive or non experimental. For example, a study which investigated the relative DQ performance of different desktop printers and materials without investigating a range of printing parameters would not be considered for inclusion. A total of 127 experimental articles were ultimately deemed directly relevant and were therefore critically analysed for the purpose of this review article.

2.4. Study characterisation

Each of the 127 studies that were identified in this systematic literature review were analysed to investigate what approaches had been used to characterise DQ. In order to analyse the experimental methods used in determining the relationship between the printing parameters and DQ metrics, each study was analysed, and the most important aspects were formatted as shown in Table 1. For each study the: ME AM machine type, slicer, materials used, optimisation method, independent variables, sample size, test artefact, dependent variables, and relationship were recorded. A comparison between the recorded studies was subsequently undertaken, which is detailed in section 4 onwards. The relationship column shows the interaction effects between the independent variables (printing parameters) and dependent variables (dimensional quality aspects). The full table with all 127 analysed studies can be found in Appendix A.

Table 1. Details of the studies included in the review.

In Table 1, the arrows (↑↓) indicate the direction of change of the independent variable. For example, “road width ↑” indicates an increase in road width. If there is a positive effect on the dependent variable, this is noted in column 10, which shows the magnitude of this relationship. A single plus sign (+) indicates that the change in the independent variable results in an increase in the dependent variable in the table. A double plus sign (++) indicates that the change in the independent variable results in a large improvement in the dependent variable. For example, for study [22], an increase in layer thickness results in a moderate improvement in DA. In study [21], a reduction in road width results in a large improvement in DA.

Two studies have been highlighted in Table 1 in order to compare the similarities and differences in their approaches and findings. Both studies [21, 22] investigated the effects that “road width” has on DA, and yet their results are not in agreement with each other. Study 21 concludes that an increase in road width results in a large reduction in DA. Conversely, Study 22 concludes that an increase in road width results in a moderate improvement in DA. Thus, the findings warrant further investigation; the findings are analysed and discussed in Section 4 and onwards. The full table in Appendix A is used as a foundation to examine the various machines, materials, and sample sizes that have been used in experimentally investigating parameter optimisation.

3. Experimental studies investigating printing parameter optimisation

3.1. Citation network

Research on ME AM’s printing parameters has seen increasing attention within the last five years as shown in Figure 3. It is widely acknowledged that the print parameters used can have a significant effect on DQ [7, 23, 24]. The advent of the RepRap movement, the expiration of Scott Crump’s patent, and lower cost hardware resulted in the proliferation of new machines being introduced into the consumer market. Figure 3 shows that there is a correlation between the increase in

![Figure 2. Systematic literature review methodology, adapted from the PRISMA principles [19, 20].](image-url)
machines and experimental studies published. Essentially, as the technology has become more ubiquitous, there has been an increase in academic attention to understanding and improving its limitations.

Of the 127 studies that experimentally investigated the DQ of printed parts, 88 were available for analysis in Web of Science's database and were subsequently imported into a CiteNetExplorer's citation network as shown in Figure 4. This software allowed the authors to visualise the citation links between the reviewed studies. The core publications in this research field as identified using the citation network are Anitha et al. [25], Sood et al. [22], Ahn et al. [26], Galantucci et al. [27], and Mahmood et al., [28].

In 2019, 12 studies that investigated DQ were published as shown in Figure 4. The 12 studies had directly cited 16 out of the 61 studies that had been published previously. This limited direct citation suggests a lack of connectivity between the studies and that each independent study is only referencing a subset of comparable extant work. This supports the need for a thorough literature review of this type, to provide a comprehensive repository of relevant work for academics in this domain.

The empirical results demonstrate that older publications have received a greater number of citations than more recent publications. Furthermore, there is shown to be a significant increase in the number of

| Study | Machine | Slicer | Materials Used | Optimisation Method/Technique or Tools | Independent Variables | Characterisation Method | Sample Size | Test Artefact | Dependent Variables | Relationship between independent and dependent variables |
|-------|---------|--------|----------------|---------------------------------------|------------------------|------------------------|-------------|---------------|---------------------|----------------------------------------------------------|
| [21]  | Maxum RP Machine | N/A | ABS | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Contour width, Raster width, Raster angle, Air gap | Mitutoyo BH303 coordinate measuring machine (CMM) | 9 samples | A square benchmark model (50 × 50 mm) with surface features | Dimensional accuracy (DA) | Contour width ↑ (GF + +) Road width ↓ (DA + +) Raster angle ↑ (SR + +) Air gap ↑ (SR + +) |
| [22]  | Vantage SE | N/A | ABS | Taguchi method, Analysis of Variance (ANOVA), signal to noise ratio, Gray Relational Analysis | Layer thickness, Build orientation, Raster angle, Road width, Air gap | Mitutoyo vernier callipers | 27 samples | Cuboid 80 × 10 × 4 mm | Dimensional accuracy (DA) | Layer thickness ↑ (DA +) Build orientation ↓ (DA + +) Raster angle ↓ (DA + +) Road width ↑ (DA + +) Air gap ↑ (DA + +) |

Figure 3. Temporal distribution of salient experimental studies identified in the literature review and timeline of notable events in the development of ME AM.
publications in recent years. A systematic review at this stage is therefore well placed to capture the most recent efforts in this field.

3.2. Experimental sample size

In each study, a particular sample size of experimental components is chosen. A larger sample size typically generates more data, which can help to increase the reliability of the results. However, greater sample sizes naturally require more time and effort to analyse. Figure 5 shows the sample sizes used in the 127 analysed studies. It can be observed that the majority of the studies used a sample size of between 1 and 30, whereas few studies had sample sizes greater than 36.

With multiple variables each having several levels, the Taguchi method is often employed in order to minimise the experimental complexity. This uses an orthogonal array to alter the variable levels with the minimal number of experimental tests. With a similar number of

Figure 4. Citation network of 88 experimental studies analysed.

Figure 5. Typical printed artefact sample size used by reviewed experimental studies.
variables and levels across studies, this tends to lead to the convergence in the number of samples at around 16 to 30 for experimental approaches such as this, as shown in Figure 5.

The majority of optimisation studies perform a number of statistical techniques to establish the effects of changing parameter values. Notably, a p value is typically calculated for each variable or combination of variables. The commonly accepted value of 0.05 is used through the studies, which denotes a statistically significant likelihood of the parameter values having the measured effect on the output variable. Higher sample sizes may help to capture smaller effects, but those observed with a p value of less than 0.05 in the studies conducted can be considered statistically significant with the sample sizes used.

In some isolated studies, either a very small or a very large number of experiments have been conducted. One study with a high number of samples is Devicharan and Garg [29]. This study printed 100 identical samples of an ABS cube; the characterisation results recommended the improvements needed in the ME AM process. Alternatively, Masović et al. [30], produced only 3 separate gear components; each gear was either printed with a different material or in a different printing direction, thus, each gear was unique. The study concluded that the printing parameters have an effect on the DA of the gears. In cases such as this where there is only a small sample size and limited statistical analysis, confidence in the results is questionable. We would strongly argue in favour of larger sample sizes for future studies in order to yield greater reliability and efficacy in the results.

3.3. Artefact geometry and size

In order to perform experimental work, each study produced an artefact for characterisation. These artefacts differed in both geometry and scale. The maxima, mean, and minima absolute dimensions of the parts produced across the studies are subsequently stated. In the X axis, the maxima and minima absolute part dimensions ranged from 270 mm to 10 mm respectively. In the Y axis, the maxima and minima absolute part dimensions ranged from 240 mm to 1 mm respectively. In the Z axis, the maxima and minima absolute part dimensions ranged from 220 mm to 3.5 mm respectively. The upper values here correspond to the largest build dimensions available on typical desktop ME AM machines. The mean absolute part dimensions in the X, Y, and Z axes are 54 mm, 31 mm, and 23 mm respectively.

It is interesting to note that on the whole, each study has developed its own bespoke test artefact in order to evaluate the impact of the variables being investigated in that particular study. Overall, there is no consistency in the artefacts used, with huge variation in both size and shape. Some of the most widely used artefacts used are the dog bone [31, 32, 33, 34] and the cube [10, 35, 36]. This lack of consistency has a significant impact on the comparability of results across the different studies. For example, Marwah et al. [37], used a rectangular benchmark part comprised of various features on the top surface, whereas Herath et al. [38], characterised a complex part with extruded and spherical geometries. Although this area has not been fully explored, some studies have suggested that dimensional accuracy and precision can depend on component geometry. For example [39], Bakar et al. demonstrated that cylindrical features give the largest dimensional error and suggested that this was as a result of machine design limitations. Furthermore, many studies use contrasting materials, machines, characterisation techniques and most importantly, printing parameters adding further potential for variability.

Several studies conclude that there would be benefit in some standardisation in the geometry and size of the test artefact (e.g. [40]) but has yet to achieve widespread adoption. However, if a standard base artefact with consistent dimensions and geometries were used in all the experimental studies, a comparison between studies is far more feasible. Without greater standardisation, it is especially difficult to perform a direct comparison between printing parameters, materials, or machines. This is arguably one of the most significant challenges for future work in order to not only compare results with confidence but also to develop meaningful meta analysis of the outputs from different researchers.

3.4. Machine types

There is a plethora of ME AM machines available in the market and this is reflected in the experimental work reviewed. The range of machines used across the studies is shown in Figure 6. Of the 127 experimental studies reviewed, 76 different machine models were used to conduct experimental investigations of DQ. Some of the most popular machines used were the Stratasys Vantage SE, Global 3D Labs Pranaam mini, and Makerbot Replicator 2X. Of the 76 different machine types used, ~97% of them were the conventional cartesian coordinate system set up rather than a delta arrangement. Although rarely documented in the studies analysed, a wide variety of Slicing software packages are available and are likely used in the experiments. The slicing software translates the 3D CAD file into instructions to drive the machine axes and each software package has a different approach to doing this. Therefore, the degree of machine software variability is likely even higher. It is important to note that each machine has its own firmware, which can influence the DA. The firmware

![Figure 6. Percentage distribution of machine types used in reviewed experimental studies.](image-url)
determines the extrusion volumetric rate and the translational velocity of the extruder head, which has a nominal velocity change threshold i.e., acceleration to deceleration profile. This is commonly known as jerk [41].

It would be challenging to compare which ME AM machines have a greater influence on the DQ of produced parts without standardising other variables such as: material; artefact design; printing parameters; build orientation; and characterisation method. None of the analysed studies have yet compared machines with standardised variables. However, it is well documented that poor DQ is a function of printing parameter selection and thus to a large degree, filament behaviour rather than the inherent design of the machine [7, 23, 24]. However, poor quality of machine components has been demonstrated to have a negative effect on produced parts [42].

3.5. Materials

A total of 12 different conventional materials were used in the 127 reviewed experimental studies. The most popular materials, as shown in Figure 7 are PLA and ABS which were used in 36% and 43% of the studies respectively. PLA and ABS are the most commercially popular ME AM materials; therefore it was to be expected that these thermoplastics would be the most widely used. Nylon was also a relatively popular material choice. PLA, ABS, and Nylon are widely used in the ME AM process due to their general ease of printing, safety, and low price point.

In addition to the conventional materials, a variety of custom and unconventional materials were used, particularly composites [43, 44, 45, 46]. The analysed studies investigated the optimum parameters for producing parts with said materials and subsequently characterised the DQ of the produced artefacts.

ME AM is heavily influenced by the choice of printing parameters, and each material behaves differently during the deposition process because of their different rheological properties. Rheological properties such as flow rate, shear rate, strength, and final material shape are considerably linked to the physical characteristics of a polymer. Some of these characteristics are density, crystallinity, and viscoelasticity. Both ABS and PLA are viscoelastic polymers, which behave in a more viscous or elastic fashion depending on the velocity in which they are deformed. However, as ABS is an amorphous polymer and PLA has a low degree of crystallinity, the melt flow behaviours of the materials differ. Particularly the temperature of the melt flows, which are influenced through viscous dissipation. Thus, resulting in both ABS and PLA having different time dependant material properties, which can consequently affect the DQ [47, 48, 49].

Furthermore, it has been demonstrated that different filament colours of the same material using constant printing parameters can also influence the DQ. This is a result of the material property differences between natural and synthetic polymers [50].

As a result, both ABS and PLA have different parameters in order to print components to the same level of DQ. Consequently, to inform the 3D printing community on how to optimise the printing parameters, the appropriate filament material must be selected according to previous studies in order to perform a direct comparison. Currently, most slicing software packages contain suggested temperatures for the selected material but do not change the nozzle path algorithm. It is therefore implicitly assumed that should these parameters be used; the geometrical performance does not differ between materials. Further work might be undertaken to elucidate if a range of materials perform in the same way for these suggested parameters.

3.6. Slicing software

The production of final components via the ME AM process requires the conversion of a 3D virtual model into machine code. This is then executed by the specific ME AM machine selected, of which there are many types as evidenced in the previous subsection. The production of machine code is handled by a so called ‘slicer’ or ‘slicing’ software package. This converts the outer surface mesh of the virtual model to a series of 2D slices which are then built up in order to produce the final component. Each of these slices is created by the combination of material extruded through the nozzle and the movement of that nozzle in the slice plane.

The choice of this toolpath and extrusion profile differs between slicer software packages. As a result, the final component’s quality characteristics are liable to influence by the slicer software used to produce the machine code. It has been demonstrated that the slicer can have a significant effect on the accuracy of the component produced. For example [51], Baumann et al., evaluated the influence of four leading slicers on the accuracy of printed components and found large differences in the measured accuracy, particularly on overhangs and smaller features. Similarly [52], Sljivic et al., compared three slicers and again found significant differences in the end result.

The slicer, or more specifically the toolpath and extrusion algorithms used, should therefore also be considered as process parameters which can be changed. This is analogous to the use of different component geometries and sizes, machines, and materials all of which, if not properly accounted for, will potentially influence the optimal print parameters. As with these other three factors, the studies once again demonstrate a wide variety of selections as demonstrated in Figure 8. This shows Ultimaker CURA to be the most popular, though more than half of the studies did not report the slicer used.

3.7. Generalisability of reviewed ME AM studies

Subsections 3.2-3.6 and Appendix A show how each study has used an entirely unique experimental set up to investigate the DQ of produced parts via parameter optimisation. Of the 127 experimental studies that

![Figure 7. Percentage distribution of materials used in reviewed experimental studies.](image)

![Figure 8. Number of slicer types used in reviewed experimental studies.](image)
were reviewed, no two studies adopted the same approach of experimental set up, i.e., machine, material, slicer, artefact, characterisation method and input variables. However, two studies \cite{53, 54} were partially analogous with their respective experimental set ups. Both studies used identical machines, materials, and slicers. They remained different in, their respective use of artefact design, characterisation methods and independent variables. Furthermore, the findings from the two studies were somewhat contrary to one another. Anunsree et al., recommended that a layer Nozzle Gap Height (NGH) of 0.15 mm improved the DQ of a printed M20 Bolt, whereas Rahman et al., concluded that a NGH of 0.2 mm improved the DQ of a standard test bar. Although the two aforementioned studies have used somewhat similar set ups, the studies cannot be directly compared, and thus the printing parameters and their interactions cannot be isolated for analysis. Differences in the experimental set up between the 127 experimental studies demonstrate that the recommendations for improving the DQ of printed parts cannot be easily generalised and are only applicable to the specific set up used in each study. Although by its very nature, some differences between studies must be present, there is an evident lack of standardisation on other factors which are not noted. This means that direct comparisons between studies highlight the current difficulty in prescribing a general solution for improving the DQ of printed parts via parameter optimisation.

However, despite this lack of consensus, it is important to recognise that each study may present recommendations which are of significance, and therefore should be synthesised to determine correlations between printing parameters and improvements to the DQ of produced parts even if not generalisable. Generally, it is widely acknowledged that a reduced NGH improves DQ, but this is not always consistently proven, this will be discussed in greater detail in the subsequent section. It is evident from this analysis that future work would beneficially focus on using analogous experimental set ups in order to present generalisable findings.

4. Printing parameters and their impact

In Table 2, Table 3, and Table 4, the authors synthesise which parameters have been shown to influence DQ within the 127 studies included in this review. A full synthesis of this nature has not previously been undertaken, and the authors believe that doing so provides some new insights into the relationship between printing parameters and DQ. We also believe that is essential for other researchers in this domain in order to ensure awareness of relevant prior work and focus attention on areas for standardisation.

| Printing Parameter | Depiction | Description | Impact on dimensional accuracy identified in analysed studies from an increase (↑ top row) or decrease (↓ bottom row) in printing parameter value. |
|-------------------|----------|-------------|----------------------------------------------------------------------------------------------------------------------------------|
| Nozzle gap height (NGH) | ![Image](102x86 to 163x119) | Also known as layer thickness, the measured displacement from the tip of the extruder nozzle to each successive layer of deposited material. NGH can also influence the defects listed: Circularity, Cylindricity, Porosity, and Surface Roughness. | ↑ [10, 22, 25, 32, 33, 35, 36, 46, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76] ↓ [12, 26, 27, 31, 34, 35, 36, 44, 45, 53, 54, 62, 77, 78, 79, 85, 81, 82, 83, 84, 85, 86, 87, 88, 89, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112] |
| Filament volumetric velocity (FVV) | ![Image](102x161 to 161x193) | Also known as feed rate, the volume of material extruded through the nozzle per unit distance travelled. FVV can also influence the defects listed: Geometrical accuracy, Porosity, and Surface Roughness. | ↑ [38, 67, 71, 106, 105, 113, 114] ↓ [73, 84, 103, 115] |
| Print head velocity (PHV) | ![Image](102x206 to 161x230) | Also known as print speed, the velocity the extruder head traversers across the build envelope during deposition and non deposition. PHV can also influence the defects listed: Circularity, Geometrical accuracy, Surface Roughness, Shrinking, and Warping. | ↑ [25, 31, 37, 53, 54, 61, 65, 72, 73, 78, 99, 100, 109, 114, 116, 117] ↓ [32, 34, 36, 68, 71, 76, 92, 106, 108, 112, 118] |
| Air Gap (AG) | ![Image](102x314 to 167x346) | The measured lateral distance between the centre points of deposited adjacent filament strands. AG can also influence the defects listed: Geometrical accuracy, Porosity, and Surface Roughness. | ↑ [12, 21, 22, 44, 86, 110, 119, 56] ↓ [22, 45, 46, 120] |
| Raster angle (RA) | ![Image](102x406 to 155x438) | The angle between deposited adjacent strands with respect to the X axis. RA can also influence the defects listed: Geometrical accuracy and Surface Roughness. | ↑ [21, 44, 60, 88, 119, 120, 121] ↓ [12, 22, 45, 46, 56, 66, 70, 78, 104, 110] |
| Road width (RW) | ![Image](102x450 to 125x482) | Also known as raster width, the width of a deposited stand, which is a function of the extruder nozzle diameter and toolpath parameters. RW can also influence the defects listed: Geometrical accuracy and Surface Roughness. | ↑ [12, 22, 45, 53, 60, 61, 66, 83, 120, 120, 121] ↓ [21, 25, 27, 36, 44, 46, 56, 63, 64, 110, 119, 122] |
| Contour width (CW) | ![Image](102x467 to 125x500) | Also known as perimeters and number of shells, the thickness of the outer wall of a printed part. CW can also influence the defects listed: Geometrical accuracy and Surface Roughness. | ↑ [10, 21, 28, 39, 46, 85, 121, 122] ↓ [10, 36, 38, 44, 65, 77, 87] |
| Contour print head velocity (CPHV) | ![Image](102x527 to 125x560) | Similar to print head velocity, this sets the velocity of the extruder head whilst depositing the contours of the part. CPHV can also influence the defects listed: Geometrical accuracy, Surface Roughness, and Warping. | ↑ [105] ↓ [67, 113] |
| Infill print head velocity (IPHV) | ![Image](102x549 to 125x582) | Similar to contour and print head velocity, this sets the velocity of the extruder tip of the extruder nozzle to each successive layer of deposited material. IPHV can also influence the defects listed: Geometrical accuracy and Porosity. | ↓ [113, 124] |
4.1. Aspects of dimensional quality

The DQ of a component is an umbrella term which encompasses a range of specific measures, whereby an error in any one of these may be considered to represent a defect. Component defects are deviations of a produced part that haven’t met the intrinsic requirements and/or nominal dimensions of the original virtual file. As previously stated, DA is one of the major aspects of DQ. DA refers to the difference between the measured part dimensions and the nominal model dimensions. By its very nature, this is one of the most significant defects and limitations of the ME AM process and an array of determinants can influence DA, primarily printing parameters. Due to the discontinuous nature of ME AM, defects such as DA are innate to the process and are recurrent [55]. Because of these inherent flaws, the ME AM process is somewhat impeded from producing ‘right first time’ end use components. The presence of these errors may potentially outweigh the benefits this technique possesses; however, efforts have been made in preventing and/or minimising these defects from transpiring [56].

It has been established from the systematic literature review, that printing parameters are known to significantly impact the DQ of printed components [12, 57, 58]. This will be discussed in greater detail in the subsequent sections. Modulation of any one of the ME AM machine’s input variables will likely result in a change to the final part. For example, increasing the NGH, also known as layer height or layer thickness, can significantly affect DQ because of its layer by layer functionality intrinsic to the ME AM process [59]. This example demonstrates how important it is to consider the printing parameters and how they may play a significant role in reducing DQ error.

4.2. Printing parameter synthesis

The printing parameters can be classified into specific types. Turner and Gold have previously characterised the printing parameters into design, process, and toolpath parameters [23]. Table 2, Table 3, and Table 4 classify printing parameters, adapted from Turner and Gold’s initial characterisation. Each table defines the printing parameter, the defects it can precipitate and the studies that have reported an improvement in part quality from an increase or decrease from the respective parameter value. If a study has determined that an increase in a printing parameter value has improved DA, said study will be in the top row with an upward arrow. Whereas, if a study has shown that a decrease in a printing parameter value has improved DA, it be in the bottom row.
with a downward arrow. For example, As NGH increases, studies including [10, 22, 25] etc. demonstrated an increase in DA. Conversely, studies [12, 26, 27] etc. demonstrated a decrease in DA.

Table 5. Environment and material choice.

| Environment       | Material | Printing Parameter | Impact on dimensional accuracy |
|-------------------|----------|---------------------|--------------------------------|
| With Enclosure    | ABS      | NGH                 | ↑ [12, 53, 54, 76, 93, 96, 103, 137] |
|                   |          |                     | ↓                              |
|                   | PLA      | NGH                 | ↑ [65, 67, 72, 75]              |
|                   |          |                     | ↓ [89, 92, 98, 102, 108, 109]   |
| Without Enclosure | ABS      | NGH                 | ↑ [10, 37, 76, 97]              |
|                   |          |                     | ↓ [36, 87, 97, 104]             |
|                   | PLA      | NGH                 | ↑ [32, 61, 97]                  |
|                   |          |                     | ↓ [31, 77, 82, 90, 91, 93, 94, 97, 100, 105, 107, 111, 112, 138] |


4.3. Dimensional accuracy

Of the 127 experimental studies reviewed in this study, 85 investigated DA. Across these studies, the relationship between all printing parameters listed in Table 2, Table 3, and Table 4 have been explored. Despite this, no clear consensus has been demonstrated. However, a universal solution that considers material, machine, artefact design and printing parameters has yet to be proposed and in any case, would necessarily be very complex.

The first known published study (to the best of the authors knowledge) that experimentally investigated accuracies of an ME AM part was reported in 1995. This study compared the measured dimensions to the nominal values of a fabricated test artefact. The material used was P300 polycrystalline (Nylon), the NGH was 0.254 mm, which was the only parameter stated, and a coordinate measuring machine was used to characterise the test artefact. The results indicated that poor accuracy was realised, specifically for average X, Y, and Z distances of medium scale features. The authors speculated that this could have been a result of the course track used [139].

Subsequent to this publication, many studies have made efforts in addressing poor DA via parameter optimisation using a range of characterisation methods and statistical techniques. One of the most popular statistical methods employed to characterise the magnitude of response variables and realise the optimal parameter settings is the Taguchi method. Of the 127 papers reviewed in this study, 52 adopted this approach. Multiple studies [22, 28, 33] have demonstrated the use of this method. Of all the parameters investigated in Table 2, Table 3, and Table 4, five parameters have been shown to significantly influence DA, thus these parameters have been analysed in greater detail. Although printing parameters such as RA, CW, IP, and ID were considered in a few studies, there is limited evidence regarding their influence on DA and the evidence seems to indicate that they have little significance. For this reason, the remainder of our analysis will focus explicitly on the five most significant parameters.

4.4. Nozzle gap height

Erni et al., and Camposeco Negrete both employed the Taguchi method for determining the optimal parameters in reducing dimensional variation from the nominal values [33, 105]. It was concluded that a NGH of 0.1 mm and 0.3 mm respectively, improved dimensional accuracy. This suggests, that the smallest NGH does not consistently improve DA. Furthermore, both studies used alternative materials, machines, parameters, and test artefacts, which can all have an effect.

Typically, a reduced NGH is known for reducing the staircase effect as the height of each step is reduced, and the nominal geometry better followed in the build direction. However, it has not been demonstrated that this same relationship holds for DA improvement. Some studies have postulated that the test artefact global height must be an integer of the NGH to ensure minimal dimensional deviation in the Z axis [34, 95]. Moreover, when the NGH was 1/4 of the nozzle diameter, DA was improved, as opposed to 1/2 the nozzle diameter, whereby gaps between layers were observed [91]. Ultimately, the NGH should not exceed 80% of the nozzle diameter [140]. Prior research has shown NGH’s effect on DA, further research is still required to optimise this parameter and its interaction effects.

4.5. Filament volumetric velocity

In addition to the Taguchi method, analysis of variance (ANOVA) coupled with signal to noise ratio (S/N Ratio) have been employed to determine the statistically significant parameters affecting the DA and measuring sensitivity of the quality investigated to enable respective parameter ranking [71]. Yadav et al., employed these methods, and thus identified that a print speed of 35 mm/s and a travel speed of 60 mm/s improved DA for a wax filament, whereas Abdul Haq et al., characterised that a print speed of 20 mm/s and a travel speed of 22 mm/s reduced dimensional error below 15% for a PCL/PLA composite [73]. This further demonstrates that neither a positive nor negative correlation between FVV and DA can be concluded.

One study investigated the flow tweak. A flow tweak (which changes material flow that induces percentage changes in strand width) when examined as an individual factor had an insignificant effect on shape fidelity when using the appropriate nozzle diameter for PLA. However, when presented as an interaction for all factor combinations using an artificial neural network, it was determined that FVV is significantly affected via NGH, flow tweak, PHV, and nozzle diameter, thus causing shape fidelity [100]. Therefore, importantly, these factors must be examined as a combination to produce reliable results.

It was also noted that higher filament volumetric velocities deposit excessive material at 90° corners at high print head velocities due to acceleration and deceleration as a result of motion changes [100]. Moreover, the extruder temperature has a significant effect on the material viscosity, causing over extrusion or under extrusion [114]. In order to optimise this parameter along with its effects, its interactions must be further investigated.

4.6. Print head velocity

In recent years, more advanced statistical techniques such as machine learning have been implemented to predict part quality characteristics. Sandhu et al., used a machine learning based prediction model to predict how PHV influences angular shrinkage of PLA parts [72]. The cross validation demonstrated that the predicted values were in good agreement with the experimental results, thus a PHV of 45 mm/s increased the DA. Shrinkage thus reduced as a result of increased PHV, as layout patterns are disturbed during slow deposition.
Durio et al., determined that a PHV of 30 mm/s reduced dimensional error with ABS. Furthermore, it was reported that PHV contributed 62.98% to model variance in the X and Y planes. Thus, this parameter should be kept at low values [36]. It is important to note, that in this study the interaction effects between PHV and the selected NGH were insignificant in the X and Y planes.

Rahman et al., employed Grey relational analysis coupled with the Taguchi method to perform a multi response analysis [54]. It was reported that a PHV of 55 mm/s improved dimensional accuracy of the ABS part while also considering the parameter interactions. An explanation as to why this value realised greater DA was not given.

One study performed manual measurements and determined the DA by subtracting the measured value from the nominal, without using statistical techniques. It was concluded that PHV did not have a significant effect on the DA using PLA. Furthermore, each parameter was characterised independently, thus ignoring their interactions. Additionally, the results presented that DA was constant for all PHVs except for a PHV of 90 mm/s. No clear trends could be established; however, it was postulated that this phenomenon might be a result of a heat transfer or a thermal gradient [92].

The studies reviewed present limited findings on the effect of PHV on DA and whether a high or low speed is recommended. However, it has been reported that a low speed can result in print deformation as the nozzle can physically interfere with the deposited material and a high speed can produce poor layer adhesion and insufficient cooling between layers [141]. Further work is required to fully understand how this parameter influences DA.

4.7. Build orientation

BO has been examined in many studies, as shown in Table 4. Although, this design parameter is known to have a significant effect on DA, this is largely dependent on the test artefact geometry, and the anisotropic effects as a result of the deposition process [66]. For example, Paul et al. [142], showed that build direction had a significant effect on the accuracy of a cylindrical test artefact. For more complex components with multiple features in a variety of directions, it may not be possible to align all features with their optimal build orientation. Regardless, a best practice guideline identified in prior studies, recommends that the DA is greatly improved if the test artefact is printed parallel to the X axis (0°) orthogonal to the Y axis (90°) or inversely [70, 135]. Alternatively, the part geometry will determine, which orientation it should be built in as the layer by layer deposition effects are inherent to this process.

4.8. Road width

The RW is a second order parameter and is a function of other primary printing parameters (such as ND, NGH, FVV, ET, and PHV), thus this has a significant influence on DA. An increase in RW generates a greater thermal gradient due to heat dissipation, which allows for shrinkage, thus enhancing DA [120]. One study reported that a lower RW can induce warping and deformation, reducing DA. Alternatively, if an increased RW is deposited, excess heat input is required, resulting in greater stress accumulation, and thus distorting the part. It was concluded that a low RW (0.4572 mm) was optimal for DA but was not a significant contributor [46]. However, Cruz Sanchez et al., reported that RW has major influence on DA and determined that a higher RW (0.71 mm) was optimal [61].

None of the above studies reported how the respective RWs were determined. Some studies came to contradictory conclusions for individual optimal parameters, even where artefact designs were similar. It is noted that despite the large body of work that has been reviewed, current machines and slicing software packages do not typically utilise their artefact geometries and printing parameter combinations that can be selected. As a result of this analysis, no clear consensus exists on which are most important and what their respective values should be. This suggests that optimisation is a complex issue and is subject to the machine and material used and the artefact being produced. Therefore, there is the need for further research to improve DA.

5. Discussion

In this review, the authors undertook a holistic approach in reviewing ME AM experimental studies that have investigated the DQ of printed parts as a function of printing parameter modulation. The authors conducted a rigorous literature review, whereby 127 studies were critically analysed as shown in Appendix A, thus determining the relationships between printing parameters and DQ errors that have been demonstrated via experimental work. As a result of this analysis, no clear consensus has been identified for any of the most important printing parameters. Many studies came to contradictory conclusions for individual optimal parameters, even where artefact designs were similar. It is noted that despite the large body of work that has been reviewed, current machines and slicing software packages do not typically utilise their findings. Across the studies included in this review many machine, material, slicer, and artefact combinations have been used to determine the optimum set of printing parameters. The lack of agreement in optimum parameter values suggests that these combinations also have an influence and should be further investigated. Without this, the current literature forms only a partial solution to DA improvement. Due to the fact that the previous experimental studies can’t be generalised, it is unknown how applicable this work is for future parameter optimisation studies. Adopting the recommendations from an individual existing study may negatively affect the results of future studies if the experimental set up is not precisely adhered to.

In this section, the authors first discuss the limitations of analysis techniques. Subsequently, the need for a standardised approach to better understand the influence of different machines, materials, and artefact geometries is examined. The benefits of understanding the morphology of the individual deposited strands are then proposed. Finally, the authors discuss the scope for future research.

5.1. Advanced techniques to characterise the printing parameter effects

There are almost an infinite number of machines, materials, artefact geometries, and printing parameter combinations that can be selected. As a result, each individual experiment, although rigorous on its own terms, only produces an answer which is accurate for the specific combination of parameters used. This significant complexity is not currently reflected in the parameter optimisation approaches in the literature. In order to best improve the DA of printed parts, an approach which captures this
inherent complexity is required. Future studies would be greatly enhanced if they were to adopt more consistent approaches to experimental design in order for there to be improved generalisability.

Currently it is recognised that printing parameter selection is of significant importance to this process as noted by ISO ANSI (International Organization for Standardization American National Standards Institute) standards [13]. Various studies have investigated the effects of printing parameters albeit, each parameter was systematically isolated and subsequently examined [61, 92, 120]. Adopting this systematic approach as opposed to analysing the combination of printing parameters does not properly represent any interaction effects. ME AM requires each printing parameter to work in combination in order to print high quality parts. Thus, to ensure accurate results, the parameters must be analysed collectively.

A range of design of experiment techniques coupled with statistical optimisation methods have been used to derive the interaction effects of printing parameter. Mohamed et al., and Jaisingh Sheoraj and Kumar both present thorough reviews of the experimental designs and optimisation techniques that have the ability to study the interaction effects between variables [146, 147]. However, both reviews proposed that better optimisation techniques need to be developed in order to address physical constraints within the process. In order to move towards a more rigorous representation of the array of independent variables possible within ME AM, new analysis techniques such as advanced mathematical modelling or machine learning technology is likely to be required.

5.2. Standardised approach of experimental methods to achieve generalisability

There is a lack of standardisation across the 127 studies analysed in this review. As discussed in section 3, studies were conducted on a wide range of machines, materials, and artefacts. This makes it challenging to compare studies directly and thus recommend a comprehensive set of parameters to optimise the DA of produced parts. The variety of optimal printing parameter values suggests that unique solutions exist for each combination of machine, material, and artefact. It is therefore important to better explore the effects of each of these on DA.

Currently, little is known about the specific effects of machine type on DA with very few studies using different machine types. Similarly, the effect of component geometry on the achievable DA has not been well covered in extant literature. However, it is more widely documented that different conventional thermoplastics require different printing parameters including that the printing parameters vary for different blends of the same thermoplastic. Polypropylene for example: the extrusion temperature can range from 165-250 degrees Celsius; NGH can vary between 0.1 mm to 0.35 mm, although this is also a function of artefact geometry [148].

The DA of the ME AM produced parts is highly dependent on the aforementioned variables. When characterising the DA of printed parts as a function of the less well explored machine, material, and artefact variables new studies which hold every other variable constant will prove beneficial and will ensure generalisability. For example, if one is investigating the effect of machine selection on DA; the material; artefact design; and printing parameters must remain unchanged on all the machines used in the experiment. Currently, the lack of standardisation across parameter optimisation studies makes such a comparison difficult. This targeted approach will provide greater insights into how poor DA is precipitated.

5.3. Implicit assumptions in slicing software

Significant efforts have been undertaken in investigating how the DA of produced parts could be improved via parameter optimisation experimentation. It can be determined that there is no clear consensus as to which combination of printing parameters can achieve this. As discussed, this is most likely a result of the inconsistent experimental methods that have been used between studies. One potential contributor to this lack of consensus is the implicit assumptions in the slicer software. Each Slicer has its own algorithm for generating the nozzle toolpath. As part of this, an effective strand width is assumed which can vary between slicers as well as depending on layer height and volumetric flow rate. If this is not controlled for, the use of different slicing software can therefore produce contradictory results and dimensional inaccuracies in artefacts. As a result, the findings from parameter optimisation studies cannot be generalised.

The relationships between slicer calculations and printing parameters must be characterised in order to account for the implicit assumptions in the software. Consequently, this could facilitate standardisation between future studies, with future experimentation being undertaken at a local strand level. Subsequent parameter optimisation studies without this generalisation are potentially unlikely to achieve impactful advancements. Thus, it is recommended that future efforts need to focus on understanding the process in greater detail, improving the underlying assumptions, and standardising the experimental methods initially at a local level.

5.4. Single strand morphologies

The studies analysed in this review have all examined the parameter effects and their interactions on the DA of a complete test artefact. By characterising the respective artefacts, the studies were able to report findings on DA. The ultimate dimensional quality of the external surface of a component is determined by the outermost boundary of each layer. Whilst all studies reviewed have considered ‘macro’ level errors, these originate from this ‘micro’ source. Thus, it is of paramount importance to experimentally investigate this underlying behaviour and variability by characterising strand morphologies. Understanding the micro level filament geometry will enable more sophisticated representations within the slicing software and reduce the need for extensive parameter optimisation.

Landmark studies, published by the Technical University of Denmark have made efforts in experimentally characterising single strand cross sections [149, 150, 151]. Initially, the authors proposed computational fluid dynamic simulations to investigate the morphology of strand cross sections. They identified that strand cross sections can significantly vary from being almost cylindrical to a flat cuboid depending on the NGH and PHV, thus influencing geometrical accuracy.

Subsequently, Serdeczny et al., validate their numerical model via experimental characterisation of single strand cross sectional measurements. As NGH is reduced, the cross sectional strand shape perpendicular to the print direction transitions from an oval shape to a cuboid with rounded corners. A NGH of 0.4 mm and PHV of 1.0 mm/s produced a rectangular strand at a width of 2.4 mm and height 0.4 mm. Whereas, a NGH of 1.2 mm and PHV of 1.0 mm/s produced a rectangular strand at a width of 1 mm and height 0.8 mm. As the PHV was reduced, a larger amount of filament was deposited for a set FVV [151]. These results are statistically significant, as they demonstrate the local dimensional variance that can be achieved via parameter modulation, thus affecting overall global part quality and geometry.

Additionally, a joint study between the Universities of Bradford and Nottingham, also measured the cross sectional perimeters of single strands [152]. The authors varied the FVV, PHV, and NGH, similar findings to the former studies were recorded. It is to be noted that all these studies performed measurements only in the plane orthogonal to the print direction, on specific printers, and only single strands were deposited. This analysis demonstrates that the underlying functions of this process are complex and require further investigation.

Another joint study, this time between the Universities of Nottingham and Loughborough present a volume conserving model, which simulates ME AM deposition [153]. This model provides a more accurate representation of material deposition as it allows for filament spreading and widening. The model results were well aligned with the experimental results. This study demonstrates how the filament behaviour and strand morphology is significantly influenced by crossover points. It is to be noted that the past three analysed studies have included numerical
models in their works. These models, provide a useful insight in how the filament can behave during deposition, however, they are not without their limitations. For example, they are seemingly only accurate during steady state and not at the starts and ends of strands during the acceleration and deceleration phases respectively.

A recent study by Golab et al., investigated the morphology of single strands along the length of the strand and multiple stands [154]. The underlying machine variability of a Prusa i3 MK3 Multi Material desktop 3D printer was shown to be in the order of ±30 microns (strand height) and ±75 microns (strand width). As opposed to 500 microns (height) and 2600 microns (width) when varying printing parameters for single strands. Multiple strands exhibited similar dimensional variations; however, the morphological defects were far more noticeable when using extreme printing parameters. Furthermore, morphological variations were observed at the beginning and ends of single and multiple strands.

The research on single and multiple strands for improving the global part DA through printing parameter optimisation is still at its nascent stage. However, the efforts made provide a promising foundation for multiple input variable optimisation at the micro scale.

### 5.5. Scope for future research

ME AM was first developed in the 1980s and has since seen a plethora in new ME AM machines, materials, and capabilities. New machines and components have subsequently improved the process; however, the parts can still exhibit poor DA. As ME AM is a relatively new manufacturing technology, this recent influx is somewhat expected. The first known published study to the best of the authors knowledge, that experimentally investigated accuracies of an ME AM part was reported in 1995 [139].

The results indicated that poor DA was realised in all three axes of medium scale features. Subsequent studies now use more sophisticated experimental techniques and provide greater insights, but further research is still required to address the challenges this technology faces.

In this review it has been demonstrated that extensive research has been undertaken to explore how the printing parameters affect part quality and DA. However, most of the studies out of the 127 reviewed, didn't consider the generalisability of their experimental methods and reported the dimensional and geometrical accuracy of a complete artefact and not the cause of the underlying variability. As an artefact is built in a layer by layer succession, it is fundamental to understand the local variation that can occur. Therefore, future research in experimentally characterising deposited stands of filament is an exciting and important area to investigate.

Few studies have made efforts in characterising the morphology of single strands as a function of printing parameter modulation. Particularly, cross sections along the length of the strand. However, there are still many areas to be investigated. To date, very few studies have investigated the cross section interactions of multiple strands [154, 155]. Furthermore, there has been little discussion of machine, slicer, and material impacts on strand morphology. Additional research in this area to gain a greater understanding of micro level geometries will enable more accurate software to be developed, thus improving the DA of ME AM.

Exploring the influence of machine, slicer, material, and artefact design using standardised experimental approaches will provide more information on the sources on DA error. Additionally, this principal should be applied to single stands. For future investigation of these aspects particularly the slicing software's approximations, the authors recommend the adoption of greater standardisation of research methods such that studies may be compared with one another and will subsequently ensure improved generalisability. The authors support the conclusion of Mohamed et al., that in order to facilitate this standardisation, an experimental framework with clear rules and guidelines would be beneficial [146].

A novel mathematical analysis technique in quantifying the interaction effects, needs to be developed to overcome the physical constraints of ME AM. The technique needs to be easily understood; have multi objective optimisation; high accuracy; the model dynamics need to both be linear and non linear; and most importantly it must have the ability to find interactions between variables. Furthermore, it must adequately deal with a large number of input variables at multiple levels.

In ME AM, there are multiple sources of error including machine design (e.g., poor alignment of axes) time effects (e.g., warping, shrinkage etc). However, errors are significantly influenced by the printing parameters, particularly at a local level. Deviations can occur in individual strand morphologies (e.g., strand road width, strand height, start and ends of strands). The deviations in strand morphology appear to be significant and are an inherent characteristic of the process. It is possible to reduce some of the effects of the variations in individual strand morphologies through optimising printing parameters. However, to ensure more significant improvements and to better understand the interactions between the molten thermoplastic and the nozzle. There may be opportunities to further investigate this critical aspect of the ME AM process.

Although, new designs are still in their nascent stage, the integration of in situ monitoring and/or image characterisation via machine learning is also an exciting prospect to improve DA dynamically.

### 5.6. Limitations of this study

This review specifically examines the DA of parts produced from the ME AM process, and not alternative AM technologies. Furthermore, this review undertakes a holistic approach and does not investigate an explicit material, printer design, or printing parameter combination. Both ABS [156] and PP [148] have been reviewed previously. In this review, the authors excluded non experimental studies, therefore, studies that used numerical models and/or simulations to characterise the DA of printed parts were not included in the review table [149, 150]. The authors explicitly focused on the DA defect type; thus, the authors did not rigorously investigate alternative defects caused by printing parameter selection. These have already been thoroughly investigated [14, 146, 148].

### 6. Conclusion

This review provides a detailed overview of the past 25 years of experimental studies that have investigated the DA of produced parts in ME AM. The authors reviewed and critically analysed 127 studies to evaluate which machines, materials, sample sizes, artefact designs, and printing parameters that have been used thus far. Furthermore, the authors synthesised which printing parameters have been shown to affect DA and their optimal values. This review has shown a lack of alignment in suggested parameter values in part due to the lack of standardisation and generalisability between studies and that parameter optimisation is intrinsically related to specific experimental methods. This does, however, reflect the complex nature of the machine, material, and artefact designs used during the ME AM process. There is seemingly a major disconnect between the work done and its dissemination into practice that users can adopt as a result of the poor level of generalisability. However, this review also provides a resource for users of ME AM to identify specific optimisation studies that may be relevant to their respective machine, material, and artefact set up.

Although there is a large amount of experimental work which characterises the DA of produced parts, the techniques employed during these would benefit from further development. In particular, the printing parameter interaction effects are not always considered when proposing parameter optimisation solutions. Similarly, many of these studies are physically constrained in their experimental scope. Ultimately, parameter optimisation studies are of use when the input assumptions aren't met in reality and/or there are inherent problems with the process itself.

In summary, some printing parameters have been shown to have a significant effect on the DA of produced parts and others less so. Typically, a reduced NGH will reduce the staircase effect, therefore the
nominal geometry is better adhered to. However, this relationship is not the same for DA improvement as it has been demonstrated that both an increase and decrease in NGH has improved DA. The effect of FVV on DA is inconclusive as this parameter cannot be analysed in isolation as its interactions with PHV are critical. However, it has been widely acknowledged that a high FVV with a low PHV can deposit excessive amounts of material per unit length and the opposite for a low FVV with a high PHV, thus the ratios need to be optimised in order to ensure DA improvement. Furthermore, a high PHV can result in poor adhesion between layers whereas a low PHV can lead to the nozzle physically interfering with deposited material. BO has been shown to have a considerable effect on DA, however, this is largely dependent on the test artefact geometry. It is recommended that if the artefact is oriented parallel to the X axis (0°) orthogonal to the Y axis (90°) or inversely, then DA is improved. The ET has a large effect on DA, but if one does not deviate from the recommended material temperature settings provided by the supplier, then theoretically the DA should not be affected. RW has a significant effect on DA. However, it is a function of ND, NGH, FVV, ET, and PHV, which is calculated in the Slicer software. Therefore, making it difficult to presently recommend what the optimal value should be as there are many variable interactions to consider. This however presents plenty of scope to investigate its effects. Overall, no general agreement on which are the most important printing parameters has been concluded and what their respective values should be. Optimisation is a complicated problem and is dependent on the machine and material used and the artefact being produced.

ME AM is an inexpensive alternative to many conventional manufacturing techniques and has the ability to realise complex geometries that would otherwise be impossible to fabricate via traditional means. Numerous research groups are making significant advancements in addressing poor DA. ME AM is a sequential layer by layer process whereby the morphology of a produced part is significantly influenced at a local level. Recent efforts have been made in characterising single deposited strands of thermoplastic by modulating the printing parameters. Developments in this area have demonstrated that local dimensional variance can occur, although further research is still required. It is recommended that a future crowd sourced experimental study should be undertaken, whereby each study participant prints single strands of filament using a Slicer's default printing parameters. All independent variables besides machine type should remain constant. The heights, widths, and areas of deposited strands should be reported and compared in order to determine the local DA that may occur. Additionally, In order to achieve real world impact, addressing the assumptions in the slicing software would enable greater standardisation and generalisation amongst users. Improving the DA of ME AM will facilitate increased adoption of this technology for industry, research, and wider society.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Funding statement

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) through the EPSRC Centre in Ultra Precision Engineering (EP/K503241/1).

Data availability statement

No data was used for the research described in the article.

Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgments

The authors would like to thank the financial support of the UK Engineering and Physical Sciences Research Council (EPSRC) through the EPSRC Centre in Ultra Precision Engineering (EP/K503241/1).
## Appendices

### Appendix A

| Study          | Machine          | Slicer | Materials Used            | Optimisation Method/ Technique or Tools | Independent Variables | Characterisation Method | Sample Size | Test Artefact                                                                 | Dependent Variables | Relationship                                                                 |
|----------------|------------------|--------|---------------------------|----------------------------------------|------------------------|-------------------------|-------------|--------------------------------------------------------------------------------|---------------------|--------------------------------------------------------------------------------|
| [139]          | FDM Statasys     | N/A    | PLA                       | Error distribution                     | N/A                    | Coordinate measuring machine (CMM) | N/A         | A square benchmark model (240 x 240 mm) with surface features                  | Dimensional accuracy N/A | Nozzle gap height ↓ (SR ++). Build orientation 70° (SR +++)                    |
| [79]           | N/A              | QuickSlice | N/A                      | Fractional factorial experiment and analysis of variance (ANOVA) | N/A                    | Contact type surface measurement system | 21 samples | Triangular prisms                                                              | Surface roughness (SR) | Nozzle gap height ↓ (SR ++). Build orientation 70° (SR +++)                    |
| [25]           | N/A              | N/A    | N/A                       | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Nozzle gap height Road width Print head velocity | Surtronic surface roughness measurement tester | 18 samples | N/A                                                                              | Surface roughness (SR) | Nozzle gap height ↓ (SR ++). Build orientation 70° (SR +++)                    |
| [136]          | Stratasys FDM2000 | N/A    | ABS                       | Measurement deviations                 | Part size Build envelope position Bed temperature | Coordinate measuring machine (CMM) | 12 samples repeated 3 times | Benchmark part with various small and large features | Dimensional accuracy (DA) | Part size (DA +). Position in the build envelope (DA ++) Bed temperature |
| [157]          | FDM Maxum RP     | N/A    | N/A                       | Direct measurement                     | Build angle            | N/A                     | 1 sample | Twisted truncheon                                                              | Surface roughness (SR) | Build angle 0/90/180 (SR +++)                                                  |
| [21]           | Maxum RP Machine | N/A    | ABS                       | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Contour width Road width Raster angle Air gap | Mitutoyo BH303 coordinate measuring machine (CMM) | 9 samples | A square benchmark model (50 x 50 mm) with surface features | Geometric forms (GF) | Contour width ↑ (GF ++). Road width ↓ (DA +). Raster angle ↓ (SR +). Air gap ↑ (SR +++) |
| [26]           | FDM Maxum        | N/A    | ABS                       | Mean surface roughness from 100 trial measurements | Nozzle gap height Surface angle | Surftest Formtracer Mitutoyo Corp., 1997 | 2 test parts | Rod with square planes axially rotated incrementally | Surface roughness (SR) | Nozzle gap height ↓ (SR +). Surface angle at 90° (SR +++)                     |
| [27]           | N/A              | N/A    | ABS                       | Full factorial experimental plan       | Tip size Road width Nozzle gap height | Non-contact optimal system Optimet MiniConoscan 3000, that combines a non-contact, single-point measuring sensor (ConoProbe 1000) | 8 samples repeated 3 times | Square base prisms 18 x 18 x 18 mm | Surface roughness (SR) | Road width ↓ (SR ++). Nozzle gap height ↓ (SR +++)                             |
| [22]           | Vantage SE       | N/A    | ABS                       | Taguchi method, Analysis of Variance (ANOVA), signal to noise ratio, Gray Relational Analysis | Nozzle gap height Build orientation Raster angle Road width Air gap | Mitutoyo vernier calliper | 27 samples | Cuboid 80 x 10 x 4 mm | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA +). Build orientation ↓ (DA +). Raster angle ↓ (DA +). Air gap ↑ (DA +) |
| [12]           | Prodigy Plus     | N/A    | ABS                       | Taguchi method, Analysis of Variance (ANOVA), signal to noise ratio | Nozzle gap height Road width Raster angle Air gap | Micrometer | 18 Samples | Cylinder ≈12.7 x 25.4 mm | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA +). Road width ↑ (DA +). Raster angle ↓ (SR +). Air gap ↑ (SR +) |

(continued on next page)
| Study | Machine | Slicer | Materials Used | Optimisation Method/Technique or Tools | Independent Variables | Characterisation Method | Sample Size | Test Artefact | Dependent Variables | Relationship |
|-------|---------|--------|----------------|----------------------------------------|-----------------------|--------------------------|-------------|--------------|---------------------|--------------|
| [39]  | Prodigy Plus | N/A | ABS | Full factorial experimental plan | Nozzle gap height, Contour width, Infill density | Touch-probe type coordinate measuring machine (CMM) (LH40, Wenzel, UK) | 6 samples | Cuboid base with extruded features on the top and side surfaces | Dimensional accuracy (DA), Infill density (DA +) |
| [60]  | Vantage SE machine | Insight FDM Software | ABS | Taguchi method, Analysis of Variance (ANOVA), signal to noise ratio, Grey Relational Analysis | Nozzle gap height, Build orientation, Raster angle, Road width, Air gap | Mitutoyo vernier calliper | 27 samples repeated 3 times | Cuboid with two holes 80 × 10 mm | Dimensional accuracy (DA), Nozzle gap height (DA +) Build orientation (DA +) Raster angle (DA +) Road width (DA +) Air gap (DA +) |
| [121] | Prodigy Plus | N/A | ABS | Design of experiments, analysis of variance (ANOVA), and signal to noise ratio | Contour width, Contour depth, Road width, Raster angle | Coordinate measuring machine (CMM) | 8 samples repeated 3 times | Spiral curve | Dimensional accuracy (DA), Contour width (DA +) Contour depth (DA +) Road width (DA +) Raster angle (DA +) |
| [158] | Prodigy FDM100 | N/A | ABS | Experimental Plan–Full factorial, Analysis Techniques–ANOVA | Build position, Nozzle gap height, Build orientation | Coordinate measuring machine (CMM) | 8 | Cylinder 100 mm tall with conical core | Dimensional Accuracy (DA), Vertical orientation best for DA. |
| [80]  | Dimension BST 768 | CatalystEx | ABS | Design of experiments | Nozzle gap height, Infill density, Support density, Stratification angle | Taylor Hobson Talysurf 6000 roughness profilometer | 40 samples | Modified cuboid | Surface Roughness (SR), Nozzle gap height (SR +) Infill density (SR +) Support density (SR +) Stratification angle (SR +) |
| [159] | MEM-300 | N/A | ABS | Experimental Plan–Taguchi, Analysis Techniques–S/N ratio | Filament width, Filament volumetric velocity, Nozzle gap height | N/A | 9 samples | 60 mm × 20 mm × 9 mm | Dimensional Accuracy (DA), Filament width (DA +), Filament volumetric velocity (DA +), Nozzle gap height (DA +) |
| [160] | FDM 1650 | QuickSlice | N/A | Experimental Plan–Taguchi, Analysis Techniques–S/N ratio, ANOVA, F-Test | Nozzle gap height, Road width, Air gap, Print head velocity | Mitutoyo BH303 CMM (DA), Taylor Hobson Surtronic 3P (SR) | 27 | Component with hole, cylinder and various parallel surfaces | Dimensional Accuracy (DA), Surface Roughness (SR), Nozzle gap height (SR +) Various relationships for DA depending on specific geometry |
| [131] | N/A | N/A | N/A | Measurements and calculated percentage difference | Build orientation, Infill density | Coordinate measuring machine (CMM) | 3 samples | Cube 40 × 40 × 40 mm, Cylinder ø30 × 50 mm, pyramid 35 × 35 × 35 mm | Dimensional accuracy (DA), Build orientation (DA +) Infill density (DA +) |
| [161] | N/A | CatalystEx | ABS | Optical measurements | Build orientation | 3D Optical Scanner | 5 samples repeated 3 times | Dog bone 150 × 20 × 4 mm | Dimensional accuracy (DA), Build orientation (DA +) |
| [132] | N/A | N/A | ABS | Manual and optical measurements | Build orientation | Coordinate measuring machine (CMM) and SEM | 16 samples | Cuboid with surface features 60 × 21.6 × 5 mm | Dimensional Accuracy (DA), Build orientation (DA +) |
| [162] | N/A | N/A | ABS | Experimental Plan–Design of experiments | Extruder temperature, Filament volumetric velocity, Print head velocity | Calliper/Observation | 8 samples | Component with variable 'bridging' sections, external dimension 14 × 18 mm | Unsupported features/layer adhesion/Quality (Q), Extruder temperature (Q +) Filament volumetric velocity (Q +) Print head velocity (Q +) |

(continued on next page)
| Study | Machine                     | Slicer | Materials Used | Optimisation Method/Technique or Tools | Independent Variables | Characterisation Method | Sample Size | Test Artefact | Dependent Variables | Relationship                  |
|-------|-----------------------------|--------|----------------|----------------------------------------|------------------------|-------------------------|-------------|---------------|----------------------|--------------------------------|
| [61]  | FoldaRap, a derivative version of the RepRap | Slic3r  | PLA            | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Nozzle gap height, Build orientation | Digital calliper | 9 samples | Repeated 2 times | Nozzle gap height ↑ (DA +) Build orientation ↑ (DA +) | Nozzle gap height ↑ (DA +) Build orientation ↑ (DA +) Road width ↑ (DA +) Print head velocity ↑ (DA +) |
| [78]  | Julia 3D printer            | Insight FDM Software | ABS            | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Nozzle gap height, Build orientation | Digital calliper | 9 samples | Cube 10 × 10 × 10 mm | Nozzle gap height ↓ (DA) Build orientation ↓ (DA +) Raster angle ↓ (DA +) | Nozzle gap height ↓ (DA +) Build orientation ↓ (DA +) Raster angle ↓ (DA +) Road width ↓ (DA) |
| [82]  | CubeX printer               | Netfabb Basic | PLA            | Dimensional and surface roughness measurements. | Nozzle gap height | Digital calliper | 3 samples | Dry skull with plastic teeth | Nozzle gap height ↓ (DA +) | Nozzle gap height ↓ (DA +) |
| [62]  | Dimension Elite Stratasys   | N/A ABS | N/A            | Design of experiments and analysis of variance (ANOVA) | Nozzle gap height | Coordinate measuring machine (CMM) and Talysurf C11 3D profler | 4 samples | Cuboid 20 × 20 × 10 mm | Nozzle gap height ↑ (DA +) | Nozzle gap height ↑ (DA +) (SR +) Infill density ↑ (DA +) (SR +) |
| [83]  | RapMan 3.0                  | Axon 2  | HIPS           | Observation | Extruder temperature | Road width | N/A | Cube 30 × 15 mm | Extruder temperature ↑ (DA +) Road width ↑ (DA +) Nozzle gap height ↓ (DA +) | Extruder temperature ↑ (DA +) Road width ↑ (DA +) Nozzle gap height ↓ (DA +) |
| [63]  | Stratasys FDM 3000          | N/A ABS | N/A            | Design of experiments and analysis of variance (ANOVA) | Nozzle gap height | Digital microscope | 8 samples | Cuboid 18 × 18 × 8 mm | Road width ↓ (DA +) Nozzle gap height ↑ (DA +) Nozzle diameter ↑ (DA +) | Road width ↓ (DA +) Nozzle gap height ↑ (DA +) Nozzle diameter ↑ (DA +) |
| [84]  | LulzBot TAZ 4               | N/A ABS | Optical Measurements | Nozzle gap height, Filament volumetric velocity | Tool microscope | N/A | Cube | Surface roughness (SR) | Nozzle gap height ↑ (DA +) Filament volumetric velocity ↑ (DA +) | Nozzle gap height ↑ (DA +) Filament volumetric velocity ↑ (DA +) |
| [160] | FDM- Dimension sst 1200es   | CatalystEx | ABS PLUS | Direct measurement | Build angle | Surface scanner | Mahr Surf MFW250 | 1 (36) Square-section twisted truncheon–36 cuboids of 10 × 30 × 30 mm | Build angle 0/90deg best | Build angle 0/90deg best |
| [138] | RepRap Prusa-Mendel i2      | Cura    | PLA            | Experimental Plan–Full Factorial DOE, Analysis Techniques–ANOVA, F-Test, p-values | Nozzle height | 3Shape D700 Laser Scanner | 81 | Component with variety of square, cylinder, cone, dome, hole features | Dimensional Accuracy (DA) Print head velocity ↑ (DA +) Nozzle gap eight ↓ (DA +) Mid level of filament volumetric velocity (105%) is best | Dimensional Accuracy (DA) Print head velocity ↑ (DA +) Nozzle gap eight ↓ (DA +) Mid level of filament volumetric velocity (105%) is best |
| [64]  | N/A                         | N/A ABS | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Nozzle gap height | N/A | Cube 10 × 10 × 10 mm | Road width ↓ (DA +) Nozzle gap height ↑ (DA +) Nozzle diameter ↓ (DA +) | Nozzle gap height ↑ (DA +) Nozzle gap eight ↓ (DA +) Mid level of filament volumetric velocity (105%) is best |
| [85]  | Pramaan mini                | Cura    | Nylon618       | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Nozzle gap height | Digital calliper | 9 samples | Cube 10 × 10 × 10 mm | Nozzle gap height ↓ (DA +) Build orientation ↓ (DA -) Shell thickness ↑ (DA +) | Nozzle gap height ↓ (DA +) Build orientation ↓ (DA -) Shell thickness ↑ (DA +) |
| [44]  | Fortus 400                  | N/A PC-ABS blend | I-Optimality Design, Analysis of Variance (ANOVA) | Nozzle gap height, Build orientation | Micrometer | 10 samples | Cube 35.5 × 3.5 mm | Dimensional accuracy (DA) Nozzle gap height ↓ (DA +) Air gap ↑ (DA +) Raster angle 90° (DA +) Build orientation 90° (DA +) Road width ↓ (DA) | Dimensional accuracy (DA) Nozzle gap height ↓ (DA +) Air gap ↑ (DA +) Raster angle 90° (DA +) Build orientation 90° (DA +) Road width ↓ (DA) |

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| Study | Machine | Slicer | Materials Used | Optimisation Method/Technique or Tools | Independent Variables | Characterisation Method | Sample Size | Test Artefact | Dependent Variables | Relationship |
|-------|---------|--------|----------------|----------------------------------------|-----------------------|------------------------|-------------|---------------|---------------------|--------------|
| [45]  | Titan   | N/A    | PC-ABS blend   | Taguchi method, Analysis of Variance (ANOVA) and response surface methodology | Nozzle gap height Road width Air gap Build orientation Raster angle | Digital calliper | 8 samples | Cuboid with rounded corners | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA +) Road width ↑ (DA +) Air gap ↓ (DA +) Build orientation 30° (DA +) Raster angle 0° (DA +) |
| [53]  | Proto Center 999 | Kisslicer Pro | ABS | Taguchi design method and Grey Relational Analysis | Nozzle gap height Road width Print head velocity Support material density | Digital calliper | 9 samples | M20 bolt | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA +) Road width ↑ (DA +) Print head velocity ↑ (DA +) Support material density (DA +) |
| [129] | FDM Mojo | N/A    | ABS            | Surface roughness measurements | Build orientation | Surface roughness tester | 7 samples | Modified cuboid with surface features 45 × 25 × 18.23 mm Surface Roughness (SR) Builds orientation 90° (SR +) | N/A |
| [164] | Ultimaker 2 | N/A    | N/A            | Experimental Plan, Fractional design, Analysis Techniques—ANOVA, p-values, Black/white box modelling | Nozzle gap height Infill density Print head velocity Extruder temperature Bed temperature Bottom layer velocity Infill speed | N/A | 82 | Component with hole, curved surface and various parallel surfaces Surface Roughness (SR), Dimensional Accuracy (DA) | N/A |
| [165] | RepRap 3D Printer | N/A    | N/A            | Print orientation, Support Geometry | Observation | 4 | Screw component, 30 mm diameter, 18 mm pitch Roundness, visual defects Roundness is improved in the vertical orientation | N/A |
| [65]  | Makerbot Replicator Z18 | Slic3r | PLA            | Fuzzy logic, Taguchi design method and signal to noise ratio | Nozzle gap height Infill density Build orientation Raster angle Road width Air gap | Mitutoyo vernier calliper | 27 samples | Cuboid 35 × 12.5 × 3.5 mm Dimensional accuracy (DA) | Nozzle gap height ↑ (DA +) Print head velocity ↑ (DA +) Infill pattern ↑ (DA +) Infill density ↑ (DA +) Number of shells ↓ (DA +) |
| [66]  | FORTUS 400 | N/A    | ABS            | Fuzzy logic, Taguchi design method, Analysis of Variance (ANOVA) and response surface methodology | Nozzle gap height Build orientation Raster angle Road width Air gap | Mitutoyo vernier calliper | 27 samples repeated 3 times | Cuboid 80 × 10 × 4 mm Dimensional accuracy (DA) | Nozzle gap height ↑ (DA +) Build orientation 0° (DA +) Raster angle 0° (DA +) Road width ↑ (DA +) Air gap ↑ (DA +) |
| [86]  | Fab@home | N/A    | poly-caprolactone (PCL) and Human Foreskin Fibroblasts (HFF) cells | Analysis of Variance (ANOVA) and imageJ | Air gap Nozzle gap height Build direction | Optical microscope | 9 samples repeated 3 times | Square grids configurations with pores Uniformity (U) Air gap ↑ (U +) Nozzle gap height ↓ (U +) Build direction X axis (U +) | N/A |
| [87]  | Pramaan mini | Cura | ABS            | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Nozzle gap height Build orientation Shell thickness | Digital calliper | 9 samples | Cube 10 × 10 × 10 mm Dimensional accuracy (DA) | Nozzle gap height ↓ (DA +) Build orientation 30° (DA +) Shell thickness ↓ (DA +) |
| [119] | Vantage SE | N/A    | ABS            | Response surface method, face centred central composite design, Raster angle Air gap Road width | Digital calliper | 20 samples | N/A | Dimensional accuracy (DA) | Raster angle 30° (DA +) Air gap ↑ (DA +) Road width ↓ (DA +) |

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| Study | Machine | Slicer | Materials Used | Optimisation Method/ Technique or Tools | Independent Variables | Characterisation Method | Sample Size | Test Artefact | Dependent Variables | Relationship |
|-------|---------|--------|----------------|----------------------------------------|-----------------------|-------------------------|-------------|---------------|-------------------|--------------|
| [88]  | Open Source printer | N/A | PLA | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Nozzle gap height, Raster angle speed, Infill density, Extruder temperature, Print head velocity | Perthometer S2 PGK surface analyser | 27 samples | Rectangular cuboid $20 \times 20 \times 5$ mm | Surface roughness (SR) | Nozzle gap height ↓ (SR) Raster angle speed (SR) Infill density ↓ (SR) Extruder temperature ↑ (SR) Print head velocity ↑ (SR) |
| [89]  | Da Vinci 1.0A | Slic3r | PLA | 3D acquisition, point cloud, and NURBS | Nozzle gap height | Triangulation-based 3D scanner | 6 samples | Cylinder $30 \times 20 \times 20$ mm | Dimensional accuracy (DA) Cylindricity (CY) Circularity (CI) | Nozzle gap height ↓ (DA) Raster angle speed (DA) Infill density (DA) Extruder temperature (DA) |
| [90]  | Prusa i3 | Cura | PLA | Manual Measurements | Extruder temperature, Print head velocity, Nozzle gap height | Digital calliper assumed | 18 Samples | Right angle part with various features extruded and embossed on said part $40 \times 16 \times 3.5$ mm | Dimensional accuracy (DA) | Extruder temperature ↓ (DA) Print head velocity (DA) Nozzle gap height ↓ (DA) |
| [91]  | Hybrid machine | Slic3r | PLA | Manual Measurements | Nozzle gap height | Scanning electron microscope and digital calliper | 3 samples | Cube $15 \times 15 \times 10$ mm | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA) |
| [128] | Makerbot Replicator | N/A | ABS | Point cloud data, statistical design of experiments and response surface regression analysis | Infill density, Extruder temperature | Laser scanning NextEngine HD laser scanner | 34 samples repeated 2 times | Based on the NAS 979 standard | Geometrical dimensioning and tolerancing (GD&T) | Infill density ↓ (GD&T) Extruder temperature ↓ (GD&T) |
| [113] | Prusa i3 Hephhestos | Slic3r & Cura | PLA | Taguchi method and Analysis of Variance (ANOVA) | Nozzle gap height, Infill density, First layer speed, Print head velocity | Micrometer | 8 samples repeated 3 times | Cube $15 \times 15 \times 15$ mm | Dimensional accuracy (DA) | Nozzle gap height (DA) Infill density (DA) First layer speed (DA) Infill print head velocity ↓ (DA) Perimeter velocity ↓ (DA) Slicer software Slic3r (DA) Extruder temperature (DA) Extrusion multiplier ↑ (DA) |
| [6]   | N/A | N/A | PC | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Nozzle diameter, Support structure, Build orientation | Coordinate measuring machine (CMM) | 24 samples | rectangular parallelepiped $44.88 \times 40 \times 80$ mm | Dimensional accuracy (DA) | Nozzle diameter ↑ (DA) Support structure (DA) Build orientation Z (DA) |
| [92]  | Makerbot Replicator 2× | N/A | PLA | Manual Measurements | Build orientation, Print head velocity, Extruder temperature, Nozzle gap height, Infill density, Infill pattern | Digital calliper & micrometre | 18 Samples | Dog bone $115 \times 19 \times 3.5$ mm | Dimensional accuracy (DA) | Build orientation (DA) Print head velocity ↓ (DA) Extruder temperature ↓ (DA) Nozzle gap height ↓ (DA) Infill density (DA) Infill pattern (DA) |
| [46]  | N/A | N/A | PC-ABS blend | IV-Optimal Response Surface Methodology (RSM), analysis of variance (ANOVA) | Nozzle gap height, Air gap, Raster angle, Build orientation | Micrometer | 60 samples | Cuboid $35 \times 12.5 \times 3.5$ mm | Dimensional accuracy (DA) | Nozzle gap height ↑ (DA) Air gap ↑ (DA) Raster angle ↓ (DA) Build orientation ↓ (DA) |

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| Study   | Machine                  | Slicer        | Materials Used | Optimisation Method/Technique or Tools | Independent Variables | Characterisation Method | Sample Size | Test Artefact | Dependent Variables | Relationship          |
|---------|--------------------------|---------------|----------------|----------------------------------------|------------------------|-------------------------|-------------|---------------|----------------------|-----------------------|
| [166]   | FDM-1200es               | CatalystEx    | ABS PLUS       | Direct measurement, ANN algorithm, trial and error, evolutionary algorithm | Build angle            | Surface scanner          | 2           | Square-section twisted truncheon-cuboids of 10 × 30 × 30 mm | Surface roughness | Build angle 0/90/180 (SR) |
| [167]   | Ultimaker                | Cura          | N/A            | Direct measurement                     | Infill geometry        | Coordinate measuring machine (CMM) | 11          | 9 component with 20 mm diameter hole, 2 component with 3 different diameter holes 10-20 mm | Dimensional Accuracy (DA) | Sun rays' design (DA+), Number of lines ↑ (DA+), Thicker lines ↑ (DA+) |
| [168]   | MakerBot                 | Makerbot Print | Full factorial | Print head velocity                     | Extruder temperature   | Coordinate measuring machine (CMM) | 9           | Embossing plates with line elements -0.2 mm-4 mm circular elements 0.2 mm-4 mm and square elements 0.2 mm-4 mm | Dimensional Accuracy (DA) | Print head velocity ↑ (DA+) |
| [93]    | Flashforge Finder        | N/A           | PLA PLA ABS    | Taguchi method, mean square error, and multi-objective error function | Extruder temperature   | Coordinate measuring machine (CMM) | 8 samples for each 3D printer | Rectangular cuboid 96.52 × 106.68 mm with various extruded and cut on the surface | Dimensional accuracy (DA) | Extruder temperature ↓ (DA+), Nozzle gap height ↓ (DA+) Infill density ↓ (DA+) |
| [77]    | 3DP WORKBENCH            | Simplify3d    | PLA            | Taguchi design method                   | Bed temperature        | Coordinate measuring machine (CMM) | 18 Samples  | ASTM D5418-07 cuboid 35 mm length, width 12.5 and height 3.5 | Dimensional accuracy (DA) | Extruder temperature ↑ (DA+), Nozzle gap height ↑ (DA+), Number of shells ↓ (DA+), Infill Pattern (DA+), Number of solid layers ↓ (DA+) |
| [28]    | Makerbot Replicator 2×   | Makerbot Print | ABS            | Taguchi design method and Signal-to-Noise-Ratio (SNR) | Chamber temperature    | Coordinate measuring machine (CMM) | 27 samples  | A square benchmark component (80 × 80 mm) with 17 extruded and embossed features on the surface | Dimensional accuracy (DA) | Chamber temperature ↓ (DA+), Extruder temperature ↑ (DA+), Number of shells ↓ (DA+), Infill shell spacing multiplier ↓ (DA+), Inset distance multiplier ↓ (DA+), Infill density ↑ (DA+) |
| [54]    | Proto Center 999          | Kisslicer Pro | ABS            | Taguchi design method and Grey Relational Analysis | Bed temperature        | Coordinate measuring machine (CMM) & SURFTEST SJ 210 | 27 samples  | Standard test bar with 6 stair step heights. | Dimensional accuracy (DA) | Bed temperature ↓ (DA, SR+), Nozzle temperature ↓ (DA, SR+), Print head velocity ↓ (DA, SR+), Infill ↑ (DA, SR+), Nozzle gap height ↓ (DA, SR+), Loops ↓ (DA, SR) |

(continued on next page)
| Study | Machine | Slicer | Materials Used | Optimisation Method/ Technique or Tools | Independent Variables | Characterisation Method | Sample Size | Test Artefact | Dependent Variables | Relationship |
|-------|---------|-------|----------------|----------------------------------------|-----------------------|------------------------|-------------|--------------|-------------------|-------------|
| [94]  | Creality 3D CR-10 | Simplify3d | PLA | Analysis of Variance (ANOVA) and imageJ | Nozzle gap height | Optical microscope | 3 samples | M10 x 1.5 screws | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA++) |
| [95]  | Commercial FDM 3D printer | N/A | PLA | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Extruder temperature Nozzle gap height Infill pattern Infill density | Digital calliper | 9 samples repeated 3 times | Based on the ASTM D638-15 standard, 100 x 19 x 6 mm | Dimensional accuracy (DA) | Extruder temperature ↓ (DA++) Nozzle gap height ↓ (DA++) Infill pattern (DA) Infill density ↓ (DA++) |
| [125] | Delta type spatial 3D printer | N/A | PLA | Cross section analysis | Extruder temperature | Optical microscope | 2 samples | Vertical thin walls 40 x 1 x 20 mm | Porosity (P) | Extruder temperature ↑ (P++) |
| [130] | Raise 3D N1 series 3D | N/A | PLA | Vision measurements | Build orientation | Rapid-I Vision Measuring System | 5 samples | Rectangular block | Dimensional accuracy (DA) | Build orientation ↑ (DA++) |
| [67]  | Gimax3D S2 | Slic3r | PLA | Taguchi design method | Extruder temperature Nozzle gap height Extruder multiplier Perimeter speed Small perimeter speed | Digital calliper | 10 samples repeated 3 times | Cuboid 70 x 48 x 4 mm with geometric features extruded and cut on the surface | Dimensional accuracy (DA) | Extruder temperature ↑ (DA++) Nozzle gap height ↑ (DA++) Extruder multiplier ↑ (DA++) Perimeter Speed ↓ (DA++) Small perimeter speed ↓ (DA++) |
| [68]  | ProtoCentre 999 | Kisslicer Pro | ABS | Taguchi method, signal to noise ratio (SNR), and Grey Relational Analysis. | Bed temperature Extruder temperature Print head velocity Infill density Nozzle gap height Number of loops | Coordinate measuring machine (CMM) and Surftest SJ-210 | 27 samples | Grinder blade ø79 mm x 25 mm | Circularity (CI) Surface roughness (SR) | Bed temperature ↑ (CL++) (SR++) Extruder temperature ↑ (CL++) (SR++) Print head velocity ↓ (CL++) (SR++) Infill density ↑ (CL++) (SR++) Nozzle gap height ↑ (CL++) (SR++) Number of loops ↑ (CL++) (SR++) |
| [114] | N/A | Cura | Wax filament | Systematic optical measurements | Extruder temperature Print head velocity. Bed temperature Filament volumetric velocity | Optical microscope | 24 samples | Wax cylinder pattern | Surface roughness (SR) | Extruder temperature ↑ (SR++) Print head velocity ↑ (SR++) Bed temperature ↑ (SR++) Filament volumetric velocity ↑ (SR++) |
| [69]  | N/A | N/A | ABS | Taguchi design method and Analysis of Variance (ANOVA) | Nozzle gap height Infill density Build orientation | MITUTOYO SJ-301 surface roughness tester | 9 samples | Cuboid 30 x 30 x 20 mm with a vertical hole | Surface roughness (SR) | Nozzle gap height ↑ (SR++) Infill density ↑ (SR++) Build orientation YZ0 (SR++) |
| [96]  | Up-Mini | N/A | ABS | Taguchi design method and Analysis of Variance (ANOVA) | Nozzle gap height Infill density Inclination Build orientation | Digital calliper | 18 Samples | Cuboid 15 x 15 x 10 mm | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA++) Infill density hollow (DA++) Inclination 0° (DA++) Build orientation 0° (DA++) |
| [43]  | Flashforge Finder | Cura | PLA/Wood | Optical measurements | Extruder temperature | Optical microscope | 6 samples | Test tube 120 x 15 x 8 mm | Dimensional accuracy (DA) | Extruder temperature ↓ (DA++) |
| [97]  | Mendel Max Konsel Mini Pura i3 | Repetier | ABS PLA | Measurement deviations | Nozzle gap height Infill density | Profile Projector DS600 Handheld roughness tester TR200 | 16 samples | Rectangular cuboid consisting of hemispheres, cubes cylinders, and slots. | Dimensional accuracy (DA) Surface roughness (SR) | Nozzle gap height ↓ (DA++) (SR++) Infill density ↓ (DA++) (SR++) |

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## Table: Independent Characterisation

| Study | Machine | Slicer | Materials Used | Optimisation Method/Technique or Tools | Independent Variables | Characterisation Method | Sample Size | Test Artefact | Dependent Variables | Relationship |
|-------|---------|--------|----------------|------------------------------------------|------------------------|-------------------------|-------------|---------------|---------------------|--------------|
| [98]  | Raise3D N2plus | N/A | PLA | Manual Measurements | Nozzle gap height | Digital calliper | 10 samples | Cylinder 15 mm x x10 mm | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA +) |
| [31]  | Monoprice Maker Select V2 | Cura | PLA | Taguchi design method and Analysis of Variance (ANOVA) | Nozzle gap height | Digital calliper | 9 samples repeated 3 times | Dog bone 90 × 10 4 mm | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA +) Print head velocity ↑ (DA +) |
| [122] | WITBOX printer | Cura | PLA | Taguchi design method and Analysis of Variance (ANOVA) | Infill Pattern Road width | Mitutoyo Surftest SJ-210 profilometer | 15 samples | Cylinder 40 mm x x30 mm | Surface roughness (SR) | Infill Pattern (SR) Road width ↓ (SR +++) |
| [99]  | N/A | N/A | PLA | Taguchi design method and Analysis of Variance (ANOVA) | Nozzle gap height | VK-X150 Laser microscope | 8 samples repeated 3 times | Cuboid | Surface roughness (SR) | Layer thickness ↓ (SR +++) Print head velocity ↑ (SR +) Infill density ↓ (SR +++) |
| [70]  | N/A | N/A | ABS PLA | Taguchi design method, Analysis of Variance (ANOVA), signal to noise ratio (SNR), grey relational grade. | Nozzle gap height | Raster angle Build orientation | Micrometre | 8 samples per material | Cuboid 35 × 12.5 × 3.5 mm | Dimensional accuracy (DA) | Nozzle gap height ↑ (DA +) Raster angle ↓ (DA +) Build orientation 0°, 90° (DA ++++) |
| [133] | uPrint SE | N/A | ABS plus | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR), grey relational grade. | Infill density Horizontal build orientation | Dial gauge | 9 samples | Tubular sample ø45 × 15 mm | Circularity (CI) | Infill density ↓ (CI +++) Horizontal build orientation ↓ (CI +++) Vertical build orientation ↓ (CI +) |
| [10]  | Pramaan mini | Cura | Taulmann Nylon | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Nozzle gap height Build orientation Shell thickness | Digital calliper | 9 samples | Cube 10 × 10 × 10 mm | Dimensional accuracy (DA) | Nozzle gap height ↑ (DA +) Build orientation 15°, 30° (DA +) Shell thickness ↓ (DA +) |
| [118] | Ultimaker 3 | Cura | TPU | Manual Measurements | Infill density Print head velocity Extruder temperature | Digital calliper | 16 samples | Rings | Dimensional accuracy (DA) | Infill density ↓ (DA -) Print head velocity ↓ (DA +) Shell thickness ↓ (DA +) Extruder temperature ↓ (DA +) |
| [134] | uPrint-SE | N/A | ABS | Taguchi design method and Signal-to-Noise-Ratio (SNR), signal to noise ratio (SNR) | Build orientation Infill density | Mitutoyo SJ-210 roughness tester | 9 samples | Bluetooth headset cover | Surface roughness (SR) | Build orientation ↓ (SR +) (DA +) Infill density ↓ (SR +) (DA +) |
| [169] | Dimension Elite Stratasys | N/A | ABSPlus-P430/ SR10-P400SR Support | Experimental Plan–Full factorial, Analysis Techniques–ANOVA, F-test, p-value | Length | 3D Systems 3D scanner | 66 | 20 mm × 20 mm × 1.5 mm–140 mm × 60 mm × 5.5 mm | Warpage/ deflection (D) | Length (D +++) Height (Intermediate value worst), LH ↓ (D +) |
| [29]  | Julia 3D Printer | N/A | ABS | Pareto analysis | Print head velocity Initial layer height, print bed surface | Observation | 100 | 1inch × 1inch × 1inch cube | Print failures/ bed adhesion | - |
| [170] | N/A | N/A | ABS | Experimental Plan–Full Factorial | Build Orientation Nozzle gap height | Contact surface (Taylor Hubson) | 15 | 20 mm × 20 mm × 10 mm | Surface roughness (SR) | "it is proposed that Layer thickness L2 = 0.2540 mm with orientation number 4 (X = 0°, Y = 0° and Z = 45°) can be considered as the highest quality of the prototype with minimum cost" |

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| Study | Machine | Slicer | Materials Used | Optimisation Method/Technique or Tools | Independent Variables | Characterisation Method | Sample Size | Test Artefact | Dependent Variables | Relationship |
|-------|---------|--------|----------------|----------------------------------------|------------------------|------------------------|-------------|---------------|---------------------|-------------|
| [171] | Picasso 250 Designer Pro, Designer X Pro | N/A | PLA, ABS, Nylon, Nylon-C, PETG, PP | N/A | Extrusion multiplier | Pressure testing, SEM | N/A | Cylinder, Cube, Pyramid, Sphere, Cone, Joined cylinder/cone | Porosity (P) | Extrusion multiplier ↑ (P↑) |
| [100] | 2D Systems CubeX Kisslicer Pro | PLA | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Nozzle gap height | 3D scanner | 27 samples | Rectangular prism 20 × 28 × 38 mm | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA↓) Flow tweak ↑ (DA↑) Print head velocity ↑ (DA↑) Build orientation ↑ (DA↑) |
| [101] | Dimension SST 1200es CatalystEx | ABS plus | Percentage volumetric error | Nozzle gap height | Digital calliper | 40 samples | Similar to ASTM D638 test artefacts | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA↓) Build orientation ↓ (DA↓) |
| [36] | 3D Cloner ST Slic3r | ABS | Taguchi design method and Analysis of Variance (ANOVA) | Road width | Digital calliper | 47 samples | Cube 10 × 10 × 10 mm | Dimensional accuracy (DA) | Road width ↓ (DA↓) Extruder temperature ↓ (DA↓) Nozzle gap height ↓ (DA↓) Print head velocity ↓ (DA↓) Infill density ↑ (DA↑) Number of contours ↓ (DA↓) |
| [102] | Profi3DMaker | N/A | Taguchi design method and Analysis of Variance (ANOVA) | Nozzle gap height | Optical measuring | Trapezium and cylinder | 2 different samples repeated 5 times | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA↓) Extruder temperature ↓ (DA↓) |
| [135] | Stratasys Mojo | N/A | Manual Measurements and surface roughness tests | Build orientation | Trapezium and cylinder | 5 samples repeated 3 times | Complex specimen | Dimensional accuracy (DA) | Build orientation X0° Y0° X90°, Y0° (DA↓) |
| [71] | Flash Forge guider 2 Flash Print | Machinable wax filament | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Build orientation | Digital calliper | 9 samples repeated 2 times | Cuboid 15 × 15 × 10 mm | Dimensional accuracy (DA) | Build orientation 90° (DA↑) Nozzle gap height ↑ (DA↑) Filament volumetric velocity ↑ (DA↑) Print head velocity ↓ (DA↓) Build orientation horizontal (DA↓) |
| [103] | Up! Mini | N/A | Data digitisation manipulation | Nozzle gap height | Digital calliper | 24 samples | Prisms and cylinders | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA↓) Filament volumetric velocity ↑ (DA↑) Build orientation horizontal (DA↓) |
| [120] | FDM Vantage SE | N/A | Response surface methodology and analysis of Variance (ANOVA) | Raster angle Air gap Road width | Digital calliper | 20 samples | Cuboid 30 × 10.5 × 10.5 mm | Dimensional accuracy (DA) | Raster angle 30° (DA↑) Air gap ↓ (DA↓) Road width ↑ (DA↑) |
| [72] | Flash Forge Guide 2 | N/A | Machine learning based prediction | Build orientation | Coordinate measuring machine (CMM) | 20 samples repeated 5 times | Trapezium 3 variations | Dimensional accuracy (DA) | Build orientation 20° (DA↑) Nozzle gap height ↑ (DA↑) Print head velocity ↑ (DA↑) |

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| Study | Machine | Slicer | Materials Used | Optimisation Method/ Technique or Tools | Independent Variables | Characterisation Method | Sample Size | Test Artefact | Dependent Variables | Relationship |
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| 104   | Zortax M200 3D | N/A | ABS | Taguchi design method, Analysis of Variance (ANOVA), and Analysis of Means (ANOM) | Raster angle, Nozzle gap height, Infill density, Infill pattern | Digital calliper | 9 samples | Cuboid with cylinder on the top surface $35 \times 15 \times 10$ mm | Dimensional accuracy (DA) | Raster angle $0^\circ$ (DA $\rightarrow$) Nozzle gap height ↓ (DA $\rightarrow$) Infill density ↑ (DA $\rightarrow$) Infill pattern Octagonal (DA $\rightarrow$) |
| 73    | FlashForge Creator Pro 2016 | N/A | PCL/PLA | Taguchi design method | Extruder temperature, Nozzle gap height, Filament volumetric velocity, Print head velocity | Coordinate measuring machine (CMM) | 20 samples | Cuboid $20 \times 20 \times 10$ mm | Dimensional accuracy (DA) | Extruder temperature ↑ (DA $\rightarrow$) Nozzle gap height ↑ (DA $\rightarrow$) Filament volumetric velocity ↑ (DA $\rightarrow$) Print head velocity ↑ (DA $\rightarrow$) |
| 38    | MakerBot | MakerBot Print | N/A | Taguchi design method | Extruder temperature, Filament volumetric velocity, Fan power, Number of shells in fill pattern | Digital calliper assumed | 16 samples | Cuboid with various features on top and bottom surfaces | Dimensional accuracy (DA) | Extruder temperature ↓ (DA $\rightarrow$) Filament volumetric velocity ↓ (DA $\rightarrow$) Fan power ↓ (DA $\rightarrow$) Number of shells ↓ (DA $\rightarrow$) Infill pattern diamond (DA $\rightarrow$) |
| 37    | Odyssey Designex $\times$2 | Cura | ABS | Taguchi design method and Analysis of Variance (ANOVA) | Nozzle gap height, Extruder temperature, Print head velocity, Infill density, Bed temperature | Mitutoyo Flexible Measuring Machine (FMM) | 19 samples | Cuboid base with extruded features on the top surfaces | Dimensional accuracy (DA) | Nozzle gap height ↑ (DA $\rightarrow$) Extruder temperature ↑ (DA $\rightarrow$) Print head velocity ↑ (DA $\rightarrow$) Infill density ↑ (DA $\rightarrow$) Bed temperature ↑ (DA $\rightarrow$) |
| 34    | 3D Volumic Stream 30 Pro | N/A | Glass reinforced polyamide (GRPA), Kevlar reinforced polyamide (KRPA) | Manual Measurements | Nozzle gap height, Print head velocity, Extruder temperature | Micrometre | 7 samples for each material repeated 3 times | Dog bone $150 \times 20 \times 4$ mm | Dimensional accuracy (DA) | Nozzle gap height ↓ (DA $\rightarrow$) Print head velocity ↓ (DA $\rightarrow$) Extruder temperature ↓ (DA $\rightarrow$) |
| 35    | Blockstec Blocks One | N/A | PLA | Taguchi design method, Analysis of Variance (ANOVA), and response surface methodology | Nozzle gap height, Print head velocity, Build orientation | N/A | 15 samples | Cube $10 \times 10 \times 10$ mm | Surface roughness (SR) | Nozzle gap height ↓ (DA $\rightarrow$) Print head velocity ↓ (DA $\rightarrow$) Build orientation ↓ (DA $\rightarrow$) |
| 105   | Wanhao Duplicator 5S Desktop | N/A | PLA | Taguchi method, Analysis of Variance (ANOVA), signal to noise ratio, Gray Relational Analysis | Nozzle gap height, Extruder temperature, Filament volumetric velocity, Perimeter speed | Digital calliper | 27 samples | 3D cube $20 \times 20 \times 20$ mm | Dimensional accuracy (DA) | Surface roughness (SR) |
| 172   | Pramaan MINI | Cura | Nylon 618 | Experimental Plan–Taguchi L9, Analysis Techniques–Fuzzy-M-COPRAS | Shell thickness, Nozzle gap height, Build orientation | Digital calliper | 9 | 10 mm × $10$ mm × $10$ mm cube | Dimensional Accuracy (DA) | Multiple outcomes simultaneously optimised |
| 173   | MakerBot Replicator 2x | MakerBot Print | Polycaprolactone (PCL) | Principal Component Analysis (PCA), Summed Standard Deviation (SSD), T-tests, p-values | Extruder temperature, Bed temperature, Print head velocity, Road width | Linkam Imaging Station | 12 | Lattice structures | Dimensional Accuracy (DA) | Print head velocity ↓ (DA $\rightarrow$) Road width ↓ (DA $\rightarrow$) |

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| [174] | Tarantula Prusa i3 | Cura | PLA | Central composite design Response surface method, ANOVA, F-Test, p-values, PSO, SOS | Nozzle gap height, Print head velocity, Extruder temperature, Outer shell speed | Micro Topper digital microscope, Mitutoyo SV-C4500 Formtracer | 46 | 125 mm × 12.7 mm × 3.2 mm | Surface Roughness (SR) | Nozzle gap height (SR+) Print head velocity (SR+) Outer Shell speed (SR+) Extruder temperature (SR+) |
| [175] | Folger Tech FDM | Repetier | ABS | Full factorial, ANOVA, F-Test, p-value, Response Surface Methodology (RSM) | Ambient temperature, Nzzle gap height, Build orientation | Mitutoyo SurfTest SJ-301 portable surface tester, Zeiss Contura G2 CMM | 29 | Pyramid components | Dimensional Accuracy (DA), Surface Roughness (SR) | Nozzle gap height ↓ (SR-) Ambient temperature ↓ (DA-) |
| [176] | N/A | N/A | Polymaker Polymooth (Polyvinyl Butyral) | Experimental Plan–Full factorial, Analysis Techniques–ANOVA, F-Test | Nozzle gap height, Print head velocity, Perimeter shells | N/A | 48 | Cuboid component | Dimensional Accuracy (DA) | Print head velocity ↑ (DA+) Nozzle gap height ↓ (DA-) |
| [30] | Stratasys Dimension SST 768 | N/A | PA, ABS | Direct measurement | Build orientation, Material | Contact measurement SURFTEST SJ-210 (Mitutoyo), Optical measurement ATOS Core 135 | 3 | Gear component, tip diameter 100.679 mm | Dimensional Accuracy (DA), Surface Roughness (SR) | Print orientation (SR+) ABS Material (DA+) |
| [177] | “Low cost FDM machine” | Cura | ABS | Experimental Plan–Taguchi, Analysis Techniques–ANOVA, S/N Ratio | Extruder temperature, Bed temperature, Print head velocity, Chamber temperature | Mitutoyo Quick Vision 404, Microtech M835 Optical Microscope | 9 | 60 mm × 30 mm × 10 mm cuboid | Warpage/deflection (D) | Bed temperature (D-) Chamber temperature (D+) |
| [178] | Raise3D N2 plus | N/A | PLA | Analysis Techniques–ANOVA, F-Test, p-values, RSM, non-dominated sorting genetic algorithm II | Nozzle diameter, Extradur temperature, Bed temperature, Filament volumetric velocity, Print head velocity, Nzzle gap height | TR300 roughness meter | 50 | N/A | Surface Roughness (SR) | Nozzle diamter ↑ (SR+) Nozzle gap height ↑ (SR+) Print head velocity ↓ (SR-) Filament volumetric velocity ↓ (SR-) |
| [115] | Katana Akimbo FDM printer | N/A | ABS PLA | Analysis of Variance (ANOVA), linear regression model | Extruder temperature, Filament Volumetric velocity, Nozzle gap height | Calliper | 30 samples | strips 0.4 × 0.4 | Dimensional accuracy (DA) | Print temperature PLA ↓ (DA-) Print temperature ABS (DA-+) Extrusion velocity PLA ↓ (DA-) Extrusion velocity ABS ↓ (DA-) |
| [33] | Stratasys F270 | N/A | ASA | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Nozzle gap height, Infill pattern, Build orientation, Printing plane, Build envelope position | Micrometre | 27 samples repeated 3 times | Dog bone ASTM D638-14 | Dimensional accuracy (DA) | Nozzle gap height ↑ (DA+) Infill pattern ↑ (DA+) Build orientation 90° (DA-+) Printing plane XY (DA+) Build envelope position middle (DA-) |
| [179] | Ultimaker 2+ | Cura | PLA | Taguchi design method | Print head velocity Cooling conditions Plate temperature | Micrometre | 9 samples | Tubular sample ×20 × 25 mm | Dimensional accuracy (DA) | Print head velocity (DA+) Cooling conditions 50% (DA+) Plate temperature (DA++) |

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| Study | Machine | Slicer | Materials Used | Optimisation Method/Technique or Tools | Independent Variables | Characterisation Method | Sample Size | Test Artefact | Dependent Variables | Relationship |
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| [124] | Commercial FDM printer | N/A | SiC/AlO reinforced LDPE | Taguchi design method and Signal-to-Noise-Ratio (SNR) | Infill density Infill angle Infill print head velocity | Digital calliper | 9 samples | Cuboid $35 \times 10 \times 10$ mm | Dimensional accuracy (DA) | Infill density ↑ (DA -) Infill angle 75° (DA -) Infill print head velocity ↓ (DA -) |
| [123] | Ultimaker Original | Cura | PLA | Taguchi design method, Analysis of Variance (ANOVA), Analysis of Means (ANOM), grey relational grade | Wall thickness Extruder temperature | Micrometer Mitutoyo Surf test SJ-210 | 9 samples | Cuboid with central recess $30 \times 30 \times 15$ mm | Dimensional accuracy (DA) Surface roughness (SR) | Wall thickness ↑ (DA +) Extruder temperature ↑ (DA +) |
| [116] | Custom delta FDM printer | N/A | ABS | Taguchi design method | Print head velocity Chamber temperature Extruder temperature | Digital calliper | 30 samples | Dog bone $90 \times 10 \times 4$ mm | Dimensional accuracy (DA) | Nozzle gap height ↑ (DA +) Print head velocity ↓ (DA -) Build orientation 0° (DA +) |
| [32] | Mono-price Maker Select V2 | N/A | PLA | Design of experiments, analysis of variance (ANOVA), and grey relational analysis | Nozzle gap height Print head velocity Build orientation | Digital calliper | 20 samples | Trazpezium 3 variations | Surface roughness (SR) Shrinkage (SA) Nozzle gap height ↓ (SR -) Angle of inclination ↓ (SR -) Print head velocity ↓ (SR -) Build orientation 0° (DA +) |
| [106] | Makerbot Replicator 2× | Cura | ABS | Response surface method, and Analysis of Variance (ANOVA) | Nozzle gap height Angle of inclination Print head velocity | Mitutoyo SJ 201P standard surface roughness measuring device | 9 samples repeated 2 times | Modified cuboid with hole $50 \times 20 \times 15$ mm | Surface roughness (SR) Raster angle ↓ (SR +) Road width ↓ (SR +) Air gap ↑ (SR +) |
| [56] | Fortus 250 mc | N/A | ABS | Taguchi method, Analysis of Variance (ANOVA) and signal to noise ratio (SNR) | Raster angle Road width Air gap | Taylor- Hobson, Surtronic 25 surface roughness measuring device | 50 | Pyramid/conical component | Dimensional Accuracy (DA) Nozzle gap height (SR -) Build orientation (SR +) Nozzle gap height (DA +) Print head velocity (DA +) Build orientation (DA +) Wall thickness (DA +) |
| [137] | 2040 Delta FDM machine | Cura | ABS | ANOVA, RSM Multi-response optimization/ desirability function | Nozzle gap height Print head velocity Build orientation Wall Thickness Extruder temperature | Mitutoyo Surf test SJ-310 Surface roughness machine, Digital calliper | 16 samples x 3 times | Multiple Strands | Dimensional Accuracy (DA) Nozzle Gap Height ↑ (DA +) Filament volumetric velocity (DA -) Print head velocity (DA +) |
| [126] | Ultimaker 3 | Cura | Technomelt PA 6910 | Extruder Temperature | Observation | 5 samples | Dog bone | Dimensional Accuracy (DA) Extruder temperature ↑ (DA +) |
| [74] | Hyrel 3D Hydra 16A printer | N/A | Ink mixture | Design of experiments (DoE), 2 full factorial experimental series, ANOVA | Nozzle Gap Height Filament volumetric velocity Print head velocity | Optical microscope | 20 \times 20 \times 20 cubes | Dimensional Accuracy (DA) Extruder temperature ↑ (DA +) |
| [127] | 3D+++ Xperia | N/A | Polymer composite | Direct measurement | Extruder Temperature Calliper/CMM | Total 7 samples, each sample had a unique material composition | 30 samples | Strips | Dimensional Accuracy (DA) ABS Extruder temperature ↑ (DA +) ABS Print head velocity ↑ (DA +) |

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| [107] | WAN-HAO Duplicator 6 | Cura | PLA | N/A | Nozzle gap height, Build orientation, Raster angle | Digital calliper | 27 samples | Dog bone | Dimensional Accuracy (DA) | Nozzle gap height ↓ (DA +) Build orientation Flat ↑ (DA +) Raster angle ↓ (DA +) |
| [108] | MakerBot z18 Print | Makerbot | PLA | Design of experiments and analysis of variance (ANOVA) | Nozzle gap height, Infill density, Extruder temperature, Print head velocity | Digital calliper | 32 samples and 32 samples | Pump connector and door hinge | Dimensional Accuracy (DA) | Nozzle gap height ↓ (DA +) Infill density ↑ (DA +) Extruder temperature ↓ (DA +) Print head velocity ↑ (DA +) |
| [109] | Ultimaker S5 | Cura | PLA | Taguchi design method, Analysis of Variance (ANOVA), signal to noise ratio (SNR), grey relational grade. | Nozzle gap height, Infill density, Infill pattern print head velocity | N/A | 27 samples repeated 2 times | Dog bone | Dimensional Accuracy (DA) | Nozzle gap height ↓ (DA +) Infill density ↓ (DA +) Infill pattern print head velocity ↑ (DA +) |
| [75] | Zaxe Z1+ xDesktop | PLA | N/A | Nozzle gap height | Digital calliper | 9 samples | Square | Dimensional Accuracy (DA) | Nozzle gap height ↓ (DA +) |
| [110] | Fortus 400 Insight | Insight Software | PC-ABS blend | integrated second-order definitive screening design (DSD) and an artificial neural network (ANN) are | Nozzle gap height, Air gap, Raster angle, Build orientation, Road width, Number of perimeters | Digital calliper | 16 samples | Cylinder 40 mm × ø10 mm | Dimensional Accuracy (DA) | Nozzle gap height ↓ (DA +) Air gap ↑ (DA +) Raster angle ↓ (DA +) Build orientation ↓ (DA +) Road width ↓ (DA +) Number of perimeters ↑ (DA +) |
| [111] | Ultimaker 2+ | Cura | PLA | N/A | Nozzle gap height, Extruder temperature | Digital calliper | 2 | Benchmark part with various small and large features | Dimensional Accuracy (DA) | Nozzle gap height ↓ (DA +) Extruder temperature ↓ (DA +) |
| [76] | Creality Ender3 | N/A | ABS | Design of experiments | Infill Density, Extruder temperature, Print head velocity, Nozzle gap height | CMM | 8 samples | Benchmark part with various small and large features | Dimensional Accuracy (DA), Surface Roughness (SR) | Infill Density (DA +) (SR +) Extruder temperature (DA +) (SR +) Print head velocity ↓ (DA +) Nozzle gap height ↓ (DA +) |
| [112] | Sigma R19 printer | N/A | PLA | Adaptive neuro-fuzzy inference systems (ANFIS) models | Nozzle diameter, Extruder temperature, Nozzle Gap Height, Print head velocity, Extrusion Multiplier | Vision measuring machine | 19 samples | Hemispherical cups ID 32 mm, OD 50 mm | Dimensional Accuracy (DA) | Nozzle diameter ↓ (DA +) Extruder temperature ↓ (DA +) Nozzle Gap Height ↓ (DA +) Print head velocity ↓ (DA +) Extrusion Multiplier ↓ (DA +) |
