Speed and accuracy evaluation of additive manufacturing machines

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Abstract
Purpose – The purpose of this paper is to establish a general method for achievable speed and accuracy evaluation of additive manufacturing (AM) machines and an objective comparison among them.

Design/methodology/approach – First, a general schematic is defined that enables description of all currently available AM machines. This schematic is used to define two influential factors describing certain parts’ properties regarding the machines’ yield during manufacturing. A test part is defined, that will enable testing the influence of these factors on the speed and accuracy of manufacturing. A method for implementing and adapting test parts is established for individual machine’s testing. This method was used to test four different machines that are predominantly used in Slovenia at the moment.

Findings – Research has proven that the machine’s yield had a predominant influence on the achievable manufacturing speeds of all the tested machines. In addition, the results have shown different ranges of achievable manufacturing speeds for individually tested machines. Test parts’ measurement results have shown comparable achievable accuracies for all the tested machines.

Research limitations/implications – Speed evaluation is based on a 2k factorial design that assumes the linearity among individual points of the experiment. This design was chosen to keep the method as simple and quick as possible, in order to perform testing on those machines otherwise used in industrial environments. Accuracy evaluation was limited by a rather small sample size of ten fabricated test parts per machine.

Practical implications – The presented evaluation method can be used on any existing or future type of AM machine, and their comparative placement regarding achievable manufacturing speed and accuracy.

Originality/value – The presented method can be used to evaluate a machine regardless of the AM technology on which it is based.

Keywords Electric machines, Velocity, Accuracy, Manufacturing industries, Production engineering, Slovenia

Paper type Research paper

1. Introduction

With an ever increasing number of different additive manufacturing (AM) machines and technologies available, it has become more difficult for potential users to choose from among them. Accurate data about certain machine’s manufacturing speed and accuracy capabilities is necessary in order to make a correct decision. Often, the only data available is potentially subjective information provided by a machine’s manufacturer. This paper presents a method of evaluating various AM machines’ speed and accuracy capabilities, thus enabling an objective and neutral comparison among them. The presented method is also presumed to be general enough to enable evaluation of future AM machines and technologies and their direct comparison with existing ones.

The presented method was developed under the hypothesis that the speed of AM systems depends mostly on the effective usage of the working space and that the height (Z-direction) of a part being processed does not affect the speed of the process, when the speed is described as a production volume per a unit of time. Such definition of speed is more general as compared to a number of layers per a unit of time, which is adequately applicable only in some of the AM systems – 3D printers mostly. Modern high-end AM systems are predominantly used for manufacturing end-user parts or in service bureaus, where the quantities of produced prototypes are rather big. The working spaces of these machines are usually filled with many, usually different parts with more or less complex geometry. The geometrical complexity, to some extent determines a working space yield, with complex parts usually containing empty spaces that cannot be filled with other parts in the build job, in order to raise the building volume’s yield. This means that the speed of the whole job depends on three influencing factors:

1 geometrical complexity of parts in the build job that influences the yield of the working space in part’s direct vicinity (“density” of a part);
2 yield of the whole working space of the AM system (“density” and number of parts in the job); and
3 the technology used in the specific AM system.
The paper describes the speed and accuracy evaluation method, which uses the first two influencing factors to determine the suitability of the AM technology (the third factor) for a specific job. The results of the experimental work presented in this paper, clearly show the differences among AM technologies tested in terms of suitability for different “density” of building jobs. It is shown that part’s geometry and building space yield significantly influences the speed of some AM systems, making them suitable for high volume production. On the other hand, some systems’ speed remains uninfluenced by the two factors, which make the technology useful for developmental and prototyping tasks only.

Furthermore, the presented method enables a quick evaluation of accuracy of the AM machines that can be used in everyday praxis. Experience show that contemporary AM systems’ reliability, in terms of acceptable (accurate) produced parts, can be very low, sometimes even at 50 percent. This is mostly due to a lack of any quality control systems installed into the AM machines by their producers. The demand will force the producers to install such systems but at the moment users have to rely on their own skills and experiences. The accuracy evaluation method presented in this paper was used to establish the accuracy levels of tested machines, but the testing part is designed in a way that enables quick and effective accuracy evaluation of every building job and is therefore used as a quality assurance tool.

2. State of the art

There are already several papers describing methods and techniques of evaluating AM machines’ performance. Some methods are based on evaluating different AM machine’s performances for building an already well defined end-user part (Chuk and Thomson, 1998; Lan et al., 2005). This kind of approach cannot guarantee a truly objective evaluation and comparison among various AM machines, due to being influenced (at least to some degree) by the requirements and properties of the part. Other researchers focus on particular type of AM machines (Han and Tseng, 2002; Han et al., 2003). These methods also include some building parameter optimization procedures and cannot be used for direct comparison to other machine types. Some papers focus on accuracy issues and implement a complex test part that also requires a complex inspection procedure (Mahesh et al., 2004). Researches focused on manufacturing speed are usually meant for build time estimation of certain machine type (Campbell et al., 2008).

Evaluation method in this paper is not meant for build time estimation on particular machine, but to establish the achievable manufacturing speed range of tested machines. These established speed ranges can then be used for direct comparison among different machines. The rather simple and quick accuracy evaluation is also included, making the presented method also a tool of quality assurance that can be used in every AM job as a mean of quality control.

3. General schematics of an AM machine

Despite a number of different AM technologies and machines available, they all need to be built rather similarly, due to the layered manufacturing principle (Drstvensek, 2004). This enables a definition of general AM machine’s schematics that can be used to present the properties of all existing machines. This definition is needed to describe the influence of AM machines’ working space on its achievable overall speed.

Every AM machine builds parts on a build tray over a known surface area. Vertical movement of the machine defines its workspace volume. Every machine also has some kind of actuator unit (laser beam source, jet nozzle, etc.) that actually forms and builds the part (Pahole et al., 2005). For a positional description, a unified coordinate system is defined as follows. The origin is placed at the centre of that work tray side where the parts are to be built. Z-axis points in the direction of vertical movement. X and Y axes are parallel to the tray’s edges. In the case of a machine with a cylindrical shaped workspace, X and Y axes orientations are unimportant, but usually correspond to the orientation of the machine’s software coordinate system (Figure 1).

A common characteristic of all AM machines is that the work tray moves vertically only as much as necessary during individual part manufacturing. Consequently, two different workspace volumes can be established. One is the maximal workspace volume defined by the tray’s dimensions and the maximal possible vertical movement of the individual machine. Additionally, the actual workspace volume for a certain build can be defined by tray dimensions, and any necessary vertical movement of its manufacturing (Figure 2).

For the purpose of this research, when a fabricated part is considered, the fabricated volume contains the volume of all parts or components manufactured in an individual machine’s run.

Figure 1 General AM machine’s schematics

Figure 2 Maximal and actual workspace volume
Fabricated volume does not include the support or carpet structure volume. The fabricated volume is contained inside the machine’s working space defined by the size of the building tray and the height of the fabricated volume, and not the maximal achievable height of the specific machine. By such definition, the comparison among different AM systems depends only on the job height and not on potential AM system’s possibilities.

4. Properties of AM machines

The research work presented in this paper focused on two characteristics of individual machines, the speed and the accuracy of manufacturing. The general agreement of AM experts that the production time of AM job depends mostly on its height can be very misleading especially, when one simplifies the meaning of time in the connection to production speed. Namely, this theory has roots in the rapid prototyping world where production is always one-off, not only in terms of individualization but also in terms of number of parts per job. With emerging number of service providers and even factories using AM systems in production processes this theory became rather useless and not only misleading. This work is based on the hypothesis that the speed of AM systems depends mostly on the effective usage of the working space and that the height (Z-direction) of a part being processed does not affect the speed of the process when the speed is described as a production volume per a unit of time. Therefore, the speed in this work is described by the value of the average manufacturing speed, calculated from the part’s volume and the time taken to fabricate:

$$\text{Average manufacturing speed} \left( \frac{\text{cm}^3}{\text{h}} \right) = \frac{\text{Part’s volume (cm}^3\text{)}}{\text{Time of manufacture (h)}}$$

This method of evaluating machine’s speed is more universal and reliable than methods that use a number of layers or millimetres of Z-direction per hour. Therefore, it enables a more objective comparison of different AM machine types.

The manufacturing accuracy is described by deviations between the finished part’s dimensions and the dimensions of its CAD model. Due to the nature of AM, it is appropriate to separate deviations according to the coordinate directions of the machine:

Deviation X = dim X – dim X CAD

Deviation Y = dim Y – dim Y CAD

Deviation Z = dim Z – dim Z CAD

It was established during the research, that the value for the average manufacturing speed is not constant for an individual machine, but depends largely on how efficiently the machine’s workspace is used during the manufacture of a certain part (run). Consequently, average manufacturing speed of a certain AM machine cannot be described by the exact value of cm$^3$ per hour, because this value depends on how efficiently the machine’s workspace is used during particular build. Instead, a certain range (conditioned by the workspace yield influence) of achievable average manufacturing speeds can be established.

In order to describe the workspace yield influence, two influential factors are used and a new geometrical entity is defined called “part’s envelope”. Part’s envelope is a block with edges (a, b, c) parallel to individual coordinate axes. The edges’ lengths are equal to the maximal part’s dimensions in individual axes, according to the part’s orientation in the machine’s workspace. The first factor is defined as the ratio between the part’s volume and the volume of the part’s envelope. It is named the “Volume Factor” and is used to describe the influences of the part’s geometry on the workspace yield (Figure 3):

$$\text{Volume ratio} = \frac{\text{Part’s volume}}{\text{Part’s envelope volume}}$$

The second factor is defined as the ratio between part’s envelope volume and part’s actual workspace volume. By definition, the envelope edge c and the vertical dimension of the actual workspace volume are always the same. Therefore, this factor can be equivalently described as a ratio between the envelope bottom surface and the work tray surface (Figure 4). It is named...
the “Tray Ratio” and is used to describe the part’s relative size regarding the machine’s workspace:

\[ \text{Tray ratio} = \frac{\text{Envelope bottom surface}}{\text{Build tray surface}} \]

According to their definitions, both factors can be calculated for an individual part and their values are always between 0 and 1.

5. Test part configuration

The main purpose of a test part is to enable the testing of certain AM machines’ speed and accuracy. Additionally, the test part’s configuration must allow some adaptation to certain AM technologies and machines (Ficko et al., 2005).

There are already several existing test parts for AM machines. Most parts are designed for accuracy evaluation only as, for example, the “SLA user group part”. Some researchers use more complex test parts that require a relatively long measuring procedure for accuracy evaluation, and are usually adapted to a specific machine (Stopp et al., 2008; Mahesh et al., 2004). Other researchers use simple parts, but conduct the testing of a single machine on a large sample, with a purpose of optimizing manufacturing position and other parameters (Dimitrov et al., 2006). These facts make the existing test parts rather unsuitable for the purpose of this research, which is to establish a relatively simple and quick method for evaluating and comparing various AM machines. Therefore, it was decided, that a new test part setup should be defined for this research, based on the following requirements. The test part must enable accuracy as well as manufacturing speed evaluation. Second, the measuring procedure must be relatively quick and adapted for coordinate measuring machine as well as a 3D optical scanner. Also, the test results must be as simple as possible, enabling the potential user to quickly compare different machines.

The basis of test part’s definition is a cube with an edge length \(a\). The cube’s edges are parallel to coordinate system’s directions and one of the corners concourses with coordinate origin. From this cube a smaller cube volume (with parallel edges) is subtracted in order to obtain a part with resulting wall thickness, in limits of \(a/10\) and \(a/3\) (Figure 5).

Both cubes have a common corner at point \((a, a, a)\). Additionally, six spheres of diameter \(D = a/3\) are defined. The spheres are arranged in three pairs. The distance direction between two spheres centres in individual pairs corresponds exactly with the individual coordinate axis. The centre distance length is equal to diameter \(D\). The spheres are labelled \(X_1\) and \(X_2\), \(Y_1\) and \(Y_2\) and \(Z_1\) and \(Z_2\). The letters stand for the coordinate axis directions and the lower number marks the sphere in individual pair that is closer to the coordinate system’s origin. Additionally, the planes \((XZ, YZ, ZY)\) are defined as normally distanced above the test part’s faces for \(D/4\). The centres of the spheres lie on corresponding planes (Figure 6).

Finally, all spheres are subtracted from the main part resulting in six partial spherical segments formed on the part. For easier manipulation of the test parts, the \(X\) and \(Y\) directional markings are applied on the part’s upper surface (Figure 7).

5.1 Application of test part for manufacturing speed evaluation

The main purpose of this part of the experiment is to evaluate the influence of previously defined volume and tray ratio on the tested machine’s manufacturing speed. This experiment is based on a simple \(2^k\) factorial design principle requiring the test to be performed at combinations of high and low levels of both influential factors. The defined test part’s setup can be used to conduct this experiment by simulating conditions at various combinations of low and high levels of both factors. The variation in volume ratio is achieved by changing the test part’s wall thickness to between the recommended limits of \(a/10\) and \(a/3\), consequently designing two test parts with volume ratios of 0.25 (low level) and 0.69 (high level). The chosen test part’s edge length for this experiment was 30 mm. The variation in tray ratio is carried out by placing different numbers of test parts on the work tray in accordance with its surface area.
In other words, a low level of tray ratio is simulated by placing sufficient number of test parts on the tray, so that a ratio value of approximately 0.1 is achieved. Accordingly, a higher level of tray ratio (0.9) is achieved by placing a greater number of test parts.

According to the influential factor’s definition, it was predicted that the part’s Z-height does not significantly influence the average manufacturing speed. In order to confirm this, three repetitions of 22 experiments were planned by vertical assembly of identical test parts. By definition, parts on Figure 8 have all the same value for volume and tray ratio and should be manufactured at the same average manufacturing speed (on the same machine). In reality, there are some deviations due to carpet structure, support manufacture or possible actuators’ cleaning time. Therefore, the purpose of this experiment’s repetition was to prove that these deviations are statistically insignificant compared to changes in average manufacturing speed due to the influence of volume and tray ratio factors.

The manufacturing time is needed, in order to calculate the average manufacturing speed of individual experiment run. During this research, manufacturing times were acquired from the software packages of tested machines. It was presumed that the software-predicted manufacturing times are accurate enough for the purpose of this experiment (Campbell et al., 2008). The first step was to prepare 12 different build tray setups in the machine’s software and read the estimated times manufacturing each setup (Figure 9).

In the next step, the actual tray ratio values and average manufacturing speeds of the test trays were calculated. Table I presents the results of EDEN330 speed evaluation.

The result analysis is based on the analysis of variance (ANOVA) method. In this research, statistical software was used in order to speed up the process. ANOVA of EDEN330 average manufacturing speed evaluation results are shown in Table II. All tested machines were evaluated using the same method, but EDEN330 results are used as an example, to explain the statistical method and significance of the assessment.

Based on ANOVA analysis of the results, the following assessments can be made:

- the model of average manufacturing speed response is statistically significant;
- volume ratio factor (A) has a significant influence on the model’s response;
- tray ratio factor (B) has a significant influence on the model’s response; and
- there is also a significant interaction effect (AB) influence on the model’s response.

Basically, the statistical significance of presented average manufacturing speed model means that the variations of response values due to the influence of both factors are much greater than the variations caused by different vertical heights of experiment repetition. This fact was proved for all tested machines as expected due to the manufacturing speed being measured in cm$^3$ of fabricated products per hour.

The next step was the establishment of a regression model that would describe the response of average manufacturing speed regarding the values of volume and tray ratio factors:

$$\text{Average manufacturing speed} = \beta_0 + \beta_1 \cdot \text{volume ratio} + \beta_2 \cdot \text{tray ratio} + \beta_{12} \cdot \text{volume ratio} \cdot \text{tray ratio}$$

Because the experiment introduced in this paper is based on $2^k$ design, a potential concern is the assumption of linearity in the factor effects. For the purpose of this experiment the $2^k$ design works quite well, even if the linearity assumption holds only very approximately. Firstly, this experiment is not intended for the establishment of a response function that will be able to predict the manufacturing speeds of individual parts exactly. Instead, the main goal is to establish the range and evaluate the limits of average manufacturing speed that are achievable by the tested machine. Second, by adding the interaction term to the main effects, this model is capable of representing some curvature in the response function. This curvature results from the twisting of the plane induced by interaction terms (Montgomery, 2001).

### 5.2 Application of a test part for manufacturing accuracy evaluation

A test part consists of three pairs of partial spherical segments that are used for manufacturing accuracy evaluation. Segments have to be measured with a 3D measuring device, either a coordinate measuring machine or a high-end optical scanner being obvious choices (Hodolic et al., 2005). The measurement results are the coordinates of those sphere centres defined by the segments. Accuracy evaluation is then based on comparing the distances between the paired spheres’ centres of a finished part and its CAD model. This method for accuracy evaluation was established with the intent of reducing the influence of surface roughness as much as possible.

Regardless of which measuring method is used, the results are always analyzed as follows. Three vectors are defined, based on coordinates of sphere centres. Vectors are used for to following reasons. First, this method enables the calculation of angles between vectors as additional evaluation of manufacturing accuracy and, secondly, by using this method the position and orientation of the measurement coordinate system (Acko, 2007) is unimportant (Figure 10).
Each vector points from a sphere centre in an individual pair that is closer to the test part’s inner corner to the sphere centre that is further away. The vector components are calculated from centres’ coordinates by the following equations:

\[
\begin{align*}
\hat{x} &= (x_2 - x_1, y_2 - y_1, z_2 - z_1) \\
\hat{y} &= (y_2 - y_1, z_2 - z_1) \\
\hat{z} &= (z_2 - z_1)
\end{align*}
\]

The next step is to calculate each vector’s length:

\[
x = \sqrt{x_x^2 + y_y^2 + z_z^2}
\]

As defined by the test part’s setup, nominal (CAD) distances between paired spheres’ centres are equal to one third of the test part’s edge or sphere’s diameter. Deviations between nominal and measured distances are used for dimensional accuracy evaluation:

\[
\text{Dimensional deviation } x = x - D \quad \text{and} \quad y = y - D
\]
Additionally, angular manufacturing accuracy is evaluated by calculating the angles between vectors, and comparing them to angles defined by the test part’s setup:

\[
\begin{align*}
\text{Angular deviation } xy(\beta) &= xy(\theta) - 90^\circ \\
\text{Angular deviation } xz(\beta) &= xz(\theta) - 90^\circ \\
\text{Angular deviation } yz(\beta) &= yz(\theta) - 90^\circ
\end{align*}
\]

6. Research results

Four different machines currently installed in Slovenia were tested with the presented method. These machines also represent four different AM technologies (Wohlers, 2008; Table III).

Testing was carried out on two test parts with minimal and maximal possible volume ratios, as defined by their setup. Manufacturing time data was acquired from the
machines’ software. Accuracy evaluation was based on ten manufactured test parts (five for each volume ratio) on each machine. The test parts’ tray layout and build parameters used for manufacturing were always optimized for best accuracy results, as defined in an individual machine’s software.

The test parts were measured using a Zeiss UMC 850 coordinate measuring machine (Figure 11).

### 6.1 EDEN 330 results

Figure 12 presents the average manufacturing speed response surface as a result of EDEN330 machine testing. The significant influence of tray and volume ratio on response can be seen, resulting in a range from 10 to 120 cm³/h of achievable average manufacturing speed. There is also a significant positive interaction of tray and volume ratio terms resulting in a twisting of the response surface. This fact is clearly presented by the curvatures of borders between interval areas (Figure 12). It is shown that volume ratio (part’s density) and tray ratio affect the building speed and that it especially depends on the effective use of the whole building tray of the machine. This is due to the printing head technology, which is very productive as compared to “scanning” (laser based systems) or even “plotting” fused deposition modelling (FDM systems) technologies.

Accuracy evaluation was based on measuring ten finished test parts. Five parts were designed with 0.25 volume ratio and five parts with 0.69. All parts were designed with 30 mm basic edges resulting in 10 mm nominal sphere centre distances. The same part setup was used throughout the research presented in this paper (Figures 13-16).

Test results show much smaller deviations in the X than the Y and Z axes. There is no notable difference between the dimensional deviations for higher and lower volume ratio parts. However, there are slightly larger angular deviations for higher volume ratio parts that can be attributed to deformations caused by material shrinkage (Brajlih et al., 2006).

### Table III Tested AM machines

<table>
<thead>
<tr>
<th>Machine</th>
<th>AM technology</th>
<th>Manufacturer</th>
<th>Installed</th>
<th>User</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDEN330</td>
<td>Polylit</td>
<td>Objet Geometries</td>
<td>2003</td>
<td>UNI Maribor</td>
</tr>
<tr>
<td>SLA 3500</td>
<td>Stereolitografy</td>
<td>3D Systems</td>
<td>1998</td>
<td>Gorenje</td>
</tr>
<tr>
<td>EOSINT P385</td>
<td>Laser sint ering</td>
<td>EOS</td>
<td>2006</td>
<td>RTCZ Hrastnik</td>
</tr>
<tr>
<td>Prodigy Plus</td>
<td>Fused deposition modelling</td>
<td>Stratasys</td>
<td>2005</td>
<td>Status</td>
</tr>
</tbody>
</table>
6.2 SLA 3500 results
SLA 3500 results show a much narrower range of achievable average manufacturing speeds than with EDEN 330. An interesting fact is the negative interaction term of volume and tray ratio. This is presented by different curvatures of borders (compared to EDEN 330 results) on a response surface (Figure 17). Tray ratio for the SLA 3500 has no or little influence on achievable manufacturing speed, especially at very dense parts, i.e., parts with high volume ratio. On the other hand, volume ratio of parts increases the manufacturing speed but the effect is much smaller as compared to EDEN 330. The results show that the SLA 3500 achieves the best performance with relatively complex parts, filling the whole working space of the machine.

Accuracy evaluation results show significantly larger deviations of test parts in X-axis then the other two. This can be attributed to the fact that the tested machine has the longest running period (approximately ten years) from among the machines evaluated during the research and that the machine’s scanning system has been worn out. It can be presumed, that the testing of a new SLA machine would yield similar deviations to the presented Y and Z results in all machine’s axes (Figures 18-21).

6.3 EOSINT P385 results
Test results show much higher average manufacturing speed values achievable by the EOSINT P385 machine than by the other tested machines. Interaction of terms has a similar positive

Figure 15 Angular deviations (EDEN330 0.25 volume ratio)

Figure 16 Angular deviations (EDEN330 0.69 volume ratio)

Figure 17 SLA 3500 average manufacturing speed response surface

Figure 18 Dimensional deviations (SLA 3500 0.25 volume ratio)

Figure 19 Dimensional deviations (SLA 3500 0.69 volume ratio)

Figure 20 Angular deviations (SLA 3500 0.25 volume ratio)
effect on response as with the EDEN330 results. The tray ratio significantly influences the manufacturing speed, whereas the volume ratio is not so important. The fact makes this machine a perfect choice for service providers or manufacturers of end parts that would always fill the machine to the top. The machine is not suitable for development departments requiring low volume or individual production of parts (Figures 22-26).

In terms of accuracy, EOSINT P385 results show somewhat larger dimensional deviations in comparison to EDEN330, but still well in within currently-accepted levels for an AM system based on laser sintering technology (Dolinsek, 2004).

**Figure 22** EOSINT P385 average manufacturing speed response surface

**Figure 23** Dimensional deviations (EOSINT P385 0.25 volume ratio)

**Figure 24** Dimensional deviations (EOSINT P385 0.69 volume ratio)

**Figure 25** Angular deviations (EOSINT P385 0.25 volume ratio)

**Figure 26** Angular deviations (EOSINT P385 0.69 volume ratio)

6.4 Prodigy plus results

By observing the response surface, it can be noted that prodigy plus achieves the lowest average manufacturing speed compared to the other tested machines (Figures 27-31). There is also no interaction term effect (either positive or negative), resulting in straight borders between average speed interval borders on a response surface. It can be seen that tray ratio makes little or no influence on the manufacturing speed. Volume ratio makes a difference but in a very low extent. This machine is predominantly meant for developmental tasks, for manufacturing of prototypes or concept models, where production of several parts at once means no advantage to the process.

Prodigy plus accuracy evaluation shows somewhat larger deviations than for the rest of the tested machines. Especially
interesting is a change in dimensional deviation behaviour between parts with lower and higher volume ratios. This can be attributed to the shrinkage condition change with a higher mass of melted material deposited.

7. Summary

The following diagrams compare the average manufacturing speeds for the tested machines. The results are separated into low and high volume ratio levels (Figures 32 and 33).

The EOSINT P385 machine achieves the highest average manufacturing speeds, regardless of both ratio values. The comparison between EDEN330 and SLA 3500 test results is
more complicated. When fabricating thin-walled parts (low volume ratio) and a lesser portion of tray surface covered (low tray ratio), SLA 3500 is able to achieve higher average manufacturing speeds than EDEN330. When considering manufacturing of parts with high volume ratio values, EDEN330 achieves higher manufacturing speeds regardless of the part’s tray ratio value. The prodigy plus machine achieves the lowest average manufacturing speeds as expected, considering that it is within a lower price range than the rest of the tested machines.

Due to the relatively small sample sizes, it is more difficult to objectively compare machines’ manufacturing accuracy. Test parts’ deviations are rather similar on all machines, with the exception of slightly bigger deviations for the prodigy plus machine. It can be assumed, that the larger X-axis deviations for the SLA 3500 machine are due to wear, and that the testing of a new SLA machine would yield much better manufacturing accuracy results.

The presented results show that different machines are able to achieve different values and ranges of average manufacturing speeds. It confirms that both ratios used to describe workspace yield significantly influence AM speed. The defined test part and the presented method of research show a capability of recognizing the differences in speeds and accuracies of various AM machines. This method presents a universal, relatively simple and highly adaptive approach to the problem of objectively evaluating speed and accuracy for AM machines. As such, it enables an objective comparison among all AM machines currently present on the market, regardless on which AM technology they are based on. Previous research mostly dealt with the accuracy evaluation of specific machine types, where machines’ speeds were not taken into account. The presented method provides a solution to fill the current research gap and can also be used for decision making and evaluation in everyday practice. For example, previous research has already established that in general LS based machines build parts faster than FDM based machines (Lan et al., 2005). This fact was also confirmed by research presented in this paper. However, the specific decision making, regarding specific machines and predicted workspace yield with which the machine will operate, can only be made after the machines are evaluated by the method presented in this paper (compare EDEN330 v. SLA3500 results). Finally, the method is presumed to be general enough to enable the evaluation of the AM machines that will be launched onto the market in future and their direct comparison to already existing ones.

Future research should be focused on evaluating as many different AM machines as possible by the presented method. This will enable their placement among already evaluated machines regarding their achievable speed and accuracy. Also, some additional criteria (parts’ mechanical properties, surface quality, etc.) or even some economical aspects (machine costs, available material costs, etc.) could be added to evaluation. This additional data could prove very useful for potential users but present an entirely different subject beyond the scope of this paper.

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