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Build Time Estimation Models in Thermal Extrusion Additive Manufacturing Processes

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Abstract

In this study, two build time estimation models (analytical and empirical) for the Material Extrusion (ME) - Fused Deposition Modelling (FDM) Additive Manufacturing (AM) process have been developed. Both models have been validated through a set of experimental case studies. The inputs required for the models include the G-Code, the volume of the part and experimentally defined coefficients related to the AM equipment. Both models are fast to run, simple in their use and provide very accurate results, since the acceleration and deceleration of the machine head is also taken into account, the effect of which play an important role in the final time estimation. The results retrieved from the analytical models are the most accurate. The outcomes of the current study are expected to assist in better production planning and energy efficiency issues related to FDM – AM processes.

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Keywords: Additive Manufacturing; Build Time Estimation; Fused Deposition Modelling;

1. Introduction

Additive Manufacturing (AM) is defined as "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining"[1]. Bikas et.al. [2] stated that AM offers many advantages, the most important of which are near zero material waste and design freedom, allowing for the manufacturing of parts with complex geometry without any extra cost. According to Berman [3], AM makes possible the manufacturing of customized parts at a much lower cost, because it eliminates the need for auxiliary equipment, like molds.

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Table 1 Nomenclature

Nomenclature	
a	*Head Acceleration*
k	*Number of times the head accelerates/decelerates*
l	*Line length*
T	*Build time*
t_1	*Time the machine head accelerates/decelerates*
t_r	*Time needed for rapid movement*
t_u	*Constant velocity deposition time*
u	*Constant Velocity of deposition*
V_r	*Rapid movement velocity*
x_1	*Distance in which accelerating movement takes place*
x_2	*Distance in which head's velocity is constant*
w_{coef}	*Distance Coefficient*
a_{coef}	*Acceleration Coefficient*

There is a wide range of materials that can be used in the different AM processes (Bikas et.al. [2]). One of the most common AM processes is the Fused Deposition Modeling (FDM) or Fused Filament Fabrication (FFF). In this process, a moving extrusion head deposits in a layer-by layer fashion thermoplastic material (ABS, PLA, Nylon, Composites etc.), after it has been heated to a temperature close to its melting point (Chryssolouris [4]).

Some of the factors that determine part quality are surface roughness, dimensional accuracy and mechanical properties. Several attempts have been made towards optimization of the AM processes by the optimization of those Key Performance Indicators (KPIs), utilizing modelling and simulation. However, according to Danforth and Safari [5], one of the most important drawbacks of AM is the low productivity of the process, which is directly connected to the Build Time (BT). On the issue of low productivity, Han et.al. [6] conducted a build time analysis of the process parameters for improving it. Gibson et.al. [7] defined the BT as the time needed for the manufacturing of a part, without taking into account design time, conversion of the CAD file to STL or the development of the G-Code. Jin et.al. [8] investigated the different impact of path generation concerning different process parameters and stated the importance of time estimation in a wide range of scientific and industrial applications. More specifically, Zhang et.al. [9] developed an adaptive estimation BT model and state that BT estimation is essential for layered manufacturing, as it affects the production process planning. Chryssolouris [4] pointed out that the cost of the final part heavily depends on the machine's operation time. Ahsan et.al. [10] studied a large amount of input data concerning part features, machine setup and production requirements that are necessary for the development of an effective BT estimation model, which are are accuracy, low simulation times and simple input data need. However, according to Jin et.al. [8], it is difficult to meet all these requirements simultaneously. Bikas et.al. [2] classified BT estimation models in three main categories: analytical, numerical and empirical. Thrimurthulu et.al. [11] studied the optimum part deposition orientation in FDM process in order to achieve better part quality or minimum built time, utilizing a numerical BT model. BT estimation models for AM have been presented in several other studies, some of which can be adapted to the FDM process [12]-[15].

The parameters that affect the BT of a part can be divided in three main categories i) The volume and mass of the part, ii) The configuration of the printer and iii) The kinematic characteristics of the printer (acceleration, deceleration, printing speed, rapid movement speed) (Table 2). However, most of the existing BT estimators do not take into account the acceleration and deceleration of the printing head, neither the rapid movements, resulting in less accurate estimations, particularly for parts with complex geometry. The models that are presented in this study take into account acceleration, deceleration and rapid movements of the printer head, resulting in estimations of higher accuracy. More specifically, in this study two models for the calculation of the kinematic characteristics (head velocity and acceleration) of the FDM AM process are presented: an analytical and an empirical one. The empirical build time model requires less input data, while the analytical is more accurate and both require low computational time.

Experiments have been conducted in order to validate the accuracy of the results of the proposed models and a comparison to the BT estimator of the FDM printer has also been made.

Table 2 Build Time parameters

	Build time parameters	
Part Volume	*Printer Kinematics*	*Printer Configuration*
Percentage fill	*Extrusion Velocity*	*Layer Thickness*
	Acceleration/ Deceleration	*Build Orientation*
	Rapid Velocity	*Infill Pattern*
	Nozzle cleaning time	*Overlap Ratio*
	Heating/reheating time	*Contours Thickness*

2. Modelling Approach

In order to develop the BT estimation models, a kinematic analysis of the path, velocity and acceleration is required. The BT estimation is implemented using two different methods: the analytical and the empirical. The data inputs of the analytical method, such as the tool path of each layer, are generated using the printer software, while the data processing has been done using the MatLab software [16]. The general equation which describes the total BT is:

$$Total\ Build\ Time = Deposition\ Time + Rapid\ Movements\ Time \tag{1}$$

The information about the total distance the head will travel and the values of constant and rapid velocity of the head is provided by the G-Code of the part. The total distance the head will travel is separated into deposition segments and in movements for the reposition of the machine head. The velocity of the head is not constant during the deposition process: Initially it is motionless, then it accelerates to extrusion velocity and then it decelerates; extrusion takes place during this time. In Figure 1, a qualitative depiction of the velocity of the head during the manufacturing of a layer can be seen. The area of the shaded regions represents the total displacement of the head.

$$Deposition\ Time = Total\ Acceleration\ Time + Moving\ Time\ With\ Constant\ Velocity \tag{2}$$

Deposition time is the time during which material is extruded by the nozzle, in order to manufacture the part. During each extrusion segment the head accelerates and decelerates when it is close to the limits of the segment, while the velocity is constant at the remaining extrusion segment (middle part). Deposition time is the sum of all the individual movements. The total acceleration time is calculated by multiplying the number of times the machine head starts or stops by the time needed for it to reach its maximum speed, which will be referred to as acceleration time, which is always the same, since the acceleration value is the same.

$$Total\ Acceleration\ Time = k * t_1 \tag{3}$$

The time in which the machine's head moves with constant velocity is the sum of all the individual extrusion time segments:

$$Moving\ Time\ With\ Constant\ Velocity\ (t_u) = t_i + t_{ii} + \ldots + t_{k/2} = \frac{x_2}{u} \tag{4}$$

$$Deposition\ Time = k * t_1 + x_2 / u \tag{5}$$

$$Rapid\ Movements\ Time = Rapid\ Distance / Rapid\ Velocity \tag{6}$$

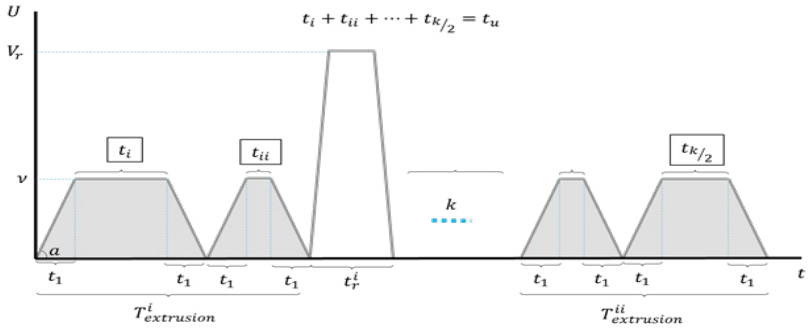

Figure 1 Head Velocity during a layer creation

2.1. Velocity and Acceleration

A test using two parts of different length has been conducted for the calculation of the velocity of the head of the machine. The movement of the head between two points in a predetermined l^i length is depicted in Figure 2. The blue shaded regions (1), (3) of Figure 1, indicate the areas in which the head accelerates/decelerates, while the unshaded area corresponds to the segment in which the head moves with a constant velocity.The coordinate x corresponds to the respective displacement of the head in each region, t corresponds to respective time, a corresponds to the acceleration/ deceleration value and u to the constant velocity.

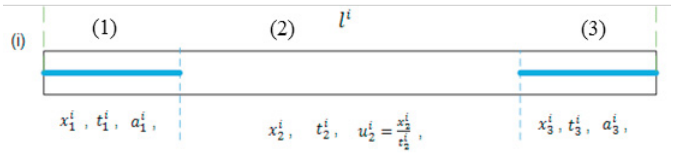

Figure 2 Head movement during a segment deposition

The time needed (T^i) for the deposition of l^ilength is:

$$T^i = t_1^i + t_2^i + t_3^i \tag{7}$$

Where T^i is the total time for line (l^i). The total length l^i between two points, is:

$$l^i = x_1^i + x_2^i + x_3^i \tag{8}$$

Assuming that: $a_1^i = -a_3^i$ then, $t_1^i = t_3^i$, $x_1^i = x_3^i$ and $u_2^i = u_2^{ii} = u$. In order to calculate the extrusion velocity for validation purposes, a second trial with different extrusion length path is required. More specifically:

$$l^i - l^i i = x_2^i - x_2^i i \tag{9}$$

Where $l^i - l^{ii}$ is a known distance, calculated from the difference of two predeterminated extrusion dinstaces.

$$T^i - T^{ii} = 0 + t_2^i - t_2^{ii} + 0 \Leftrightarrow T^i - T^{ii} = (x_2^i)/(u_2^i) - (x_2^{ii})/(u_2^{ii}) \tag{10}$$

Where $T^i - T^{ii}$ is the measured time difference from two predeterminated extrusion lengths.

$$u = (l^{i} - l^{ii}) \big/ (T^{i} - T^{ii}) \tag{11}$$

The surface area of the diagram of $u(t)$ versus time represents the total displacement of the head.

$$l_{i} = ((T^{l^{i}} - 2 * t_{1}) + T^{(l^{i})} \big/ 2) * u \tag{12}$$

$$t_{1}^{i} = (u * T^{l^{i}} - l^{i}) \big/ u \tag{13}$$

$$(13) \Rightarrow a_{1}^{i} = u^{2} \big/ u * T^{(l^{i})} - l^{i} \tag{14}$$

Equation (11) has been utilized for the experimental calculation of the constant velocity of the head, equation (13) for the calculation of the acceleration time and equation (14) for the calculation of acceleration value.

2.2. Analytical Build Time Model

An algorithm has been developed which identifies all the motions of the extrusion head, using as input the G-Code of the part. Rapid velocity time is calculated by dividing the rapid distances with the rapid velocity using Equation (6). The deposition time (Equation (5)) is calculated by summing the total acceleration time (Equation (3)) and the extrusion time with constant velocity (Equation (4)). Finally, the total build time is calculated by summing the rapid movement time and the deposition time (Equation (1)). In Figure 3 the flowchart of the developed algorithm is presented.

The developed MatLab algorithm is capable of calculating two sets of results. The first set concerns the characteristics of the part, such as the deposition distances and the rapid distances with the corresponding velocities; while the second set refers to the characteristics of the movement, which are directly connected to the kinematic characteristics of the printer. The total build time of a part is affected by the velocity that is used during material deposition, the magnitude of the acceleration and deceleration and the value of the rapid velocity. The variables used in the MatLab algorithm are the extruder velocity (extrusion velocity and rapid velocity), the magnitude of acceleration and deceleration (during the extrusion), the total distance (which is divided in rapid velocity distance and extrusion distance) and the total build time.

2.3. Empirical Build Time Model

The empirical model takes into account the geometric features of the part and the geometric features of the extruded filament. The distance the machine head has to go through in order to manufacture a layer is calculated by multiplying the area of the layer with a distance coefficient (w_{coef}). The desired percentage fill of the part affects the value of the distance coefficient. The number of times the head accelerates is estimated by multiplying an acceleration coefficient (a_{coef}) with the estimated head distance. The BT of a layer is calculated by dividing the distance the head travels with the respective velocity and adding the estimated delay from acceleration/deceleration, which is calculated by multiplying the number of times that the head accelerates/decelerates with the time t_1^i needed for the head to accelerate/decelerate. Finally, the total BT of a part is calculated by summing the BT needed for all the layers of the part. The BT estimation can become more accurate by increasing the accuracy in the calculation of the surface area of each layer. More specifically, this can be achieved by separating in the calculations of the percentage fill of the contour and the infill of the part. By separating the motion of the head into contours (100 % fill) and inner fill (selection of the AM machine operator), a better build time estimation can be achieved. The main equations of the empirical BT estimation model follow:

$$T_{total} = T_{layer} * Number\ of Layers \tag{15}$$

$$T_{total} = \left(\frac{Surface\ Area * w_{coef}}{Extrusion\ Velocity} + Head\ Distance * a_{coef} * t_1\right) * \left(\frac{Part\ Height}{Layers\ Thickness}\right) \tag{16}$$

Measurements were made in six different basic geometric parts, in order to identify the coefficients for the head movement for each layer individually. Test parts with different 2D sections have been used: three square parts (10x10 mm, 30x30 mm and 50x50 mm), two orthogonal parallelograms (40x20 mm, 50x20 mm) and a circular one (20mm radius). The screen caliper software [17] has been used to identify the extruded distances in the basic 2D geometries. The measured distances from the screen caliper software has been verified with the developed algorithm using inputs directly from G-Code. The resulted coefficients can be seen in Figure 4.

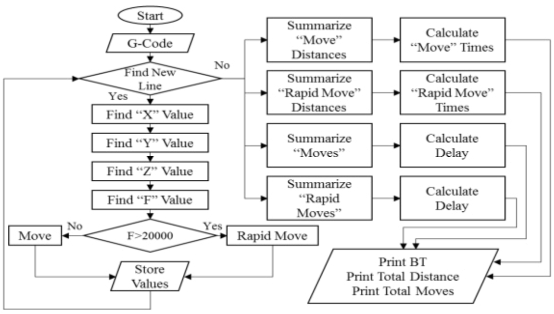

Figure 3 Analytical Build Time Model Flowchart

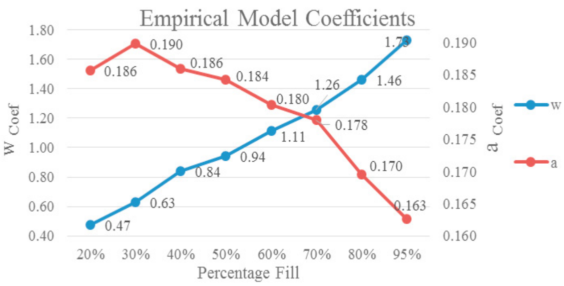

Figure 4 The coefficients of the 2.3. Empirical Build Time Model versus the percentage of the fill

3. Results and Discussion

The developed BT estimation models require the identification of the kinematic properties of the FDM AM equipment. The machine in which the experiments have been performed is the *3D Touch* by *Bits from Bytes* [18] and ABS filament with thickness of 3 mm has been used. The *Axon2* slicing software has been utilized for the G-Code generation and the tool path determination. A GoPro Hero 4 camera mounted on the frame of the printer, with resolution 848x480 at 240 frames per second, has been used for the capturing of the head motion. The time difference between two frames has been calculated at 4.16 ms. The video processing, as well as for the determination of the kinematic features, has been done using *MovieShop Framer video analysis software* [19]. The experiments have been conducted four times in order to minimize measurement errors. Calibration experiments have been conducted, using simple straight line parts of 250mm and 200mm length, so as to determine the kinematic characteristics of the AM equipment needed in the equations (17), (18) and (19). Finally, validation experiments have been conducted, using the CAD designs that can be seen in Figure 5.The results of the analytical model are presented in Table 3 and in Figure 6; it can be observed that they are closer to the experimental values than those of the Axon2 software. The average deviation of the Axon2 software from the experimentally measured data is 7.2%, while the analytical model of this study deviates 1.7 %.

A comparison has been made in order to identify the contribution of the acceleration/deceleration to the build time estimation: In the first case the accelerations and decelerations were taken into account, whereas, in the second one, the velocity of the head has been assumed to be constant. Table 3 illustrates the time differences between the experimentally measured time and the estimations in which acceleration is taken or not taken into account accordingly. The importance of the correlation between the complexity of the tool path for each layer and the contribution of the acceleration/deceleration in the total build time has to be noted. More specifically, parts 2, 4, 6 (Turbine, Spur Gear, Test Gear) have higher path complexity compared to 1, 3, 5 (Disk, Hinge, Feeder) parts. In those complex parts, the contribution of the acceleration exceeds 20% of the total build time for these three parts.

The experimental results of the empirical BT model, in which the distance and acceleration coefficients have been used, are presented in Table 4 and in Figure 7. Five validation experiments with simple part geometry have also been conducted. Parts with simple geometry were chosen in order to reduce the calculation complexity of the parts surface area. The average build time estimation deviation is 4.2% compared with the experimentally measured build time.

Table 3 Analytical Build Time Model results and comparison to experimental values

	Part	Experimentally measured time	Axon2	Difference between Axon2/ measured time	Analytical Model	Difference between Analytical Model/ measured time	Analytical Model ($a_1 = 0$)	Contribution of a_1 in BT
1	Disk	00:36:00	00:39:00	8.33%	00:35:48	0.56%	00:34:24	4.07%
2	Turbine	02:52:00	02:34:00	10.47%	02:53:00	0.58%	02:20:12	23.57%
3	Hinge	03:10:00	03:04:00	3.16%	03:07:00	1.58%	02:48:37	10.65 %
4	Spur Gear	03:58:00	03:36:00	9.62%	04:12:00	5.44%	03:18:00	27.27%
5	Feed	05:31:00	05:22:00	2.72%	05:29:00	0.60%	05:08:00	6.82%
6	Test Gear	06:51:00	06:15:00	8.76%	06:56:00	1.22%	05:28:00	26.44%

The main advantage of the empirical BT model is that it is capable of estimating the BT of a part without the need to use the CAD of the part as input; it can calculate the BT using only the surface area of the slices of the part and the desired percentage fill. The calibration of the empirical model is a simple and fast procedure, when the developed analytical algorithm is used for the determination the needed coefficients.

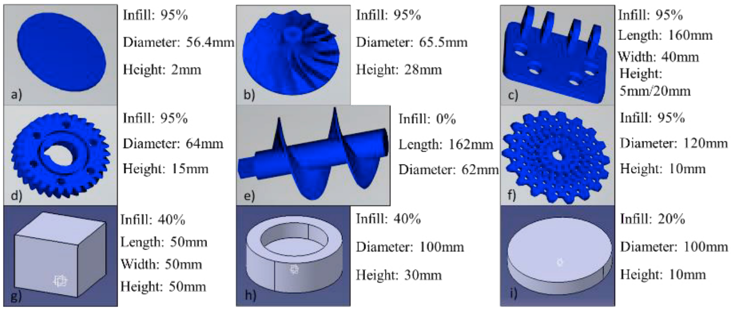

Figure 5 Validation Experiments Parts Designs

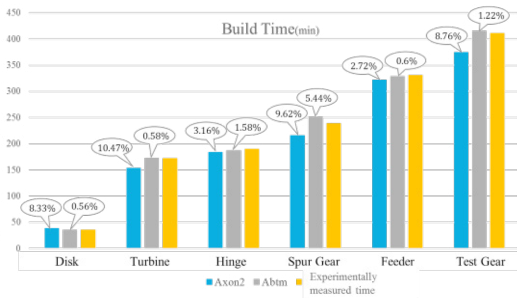

Figure 6 Analytical Build Time Model results and comparison to experimental values

4. Conclusion

In this paper, two build time estimation models have been developed, in which the contribution of acceleration and deceleration has been taken into account. Both BT models have been experimentally tested and the following can be concluded:

- Both BT models are more accurate than the BT estimator of the AM machine that was used in the experiments, which does not take into account the exact value of acceleration/deceleration of the printer's head.
- The accuracy of the analytical model is the highest between the compared estimators, being very close to the experimentally measured results, with a relative error in the scale of 1% in most of the experiments, whereas the relative error of AM machine BT estimator is in the scale of 5-10%.
- In the selection of the infill pattern, the path complexity should be taken into account, as it has been observed that the contribution of acceleration becomes more important in the build time of a part when the path complexity is very high.

As far as future work is concerned, the first step would be the development of an analytical energy consumption estimation model that will be connected to the kinematic simulation model that has been presented in this study. Also, further research could be done on the connection of the acceleration of the head and the dimensional accuracy. Finally, the time needed for the re-heating the extruders, in case of multiple interchangeable extruders, could be included in the build time estimator.

Table 4 Empirical Build Time Model results and comparison to experimental values

	Part	*Experimentally measured time*	*Empirical Model*	*Deviation*
1	Disk	00:36:00	00:38:00	5,3%
2	Cube	07:43:00	07:43:32	0,2%
3	Hinge	03:10:00	03:20:58	5,5%
4	Case	08:34:00	08:19:26	3,0%
5	Disk2	05:11:00	04:50:35	7,2%

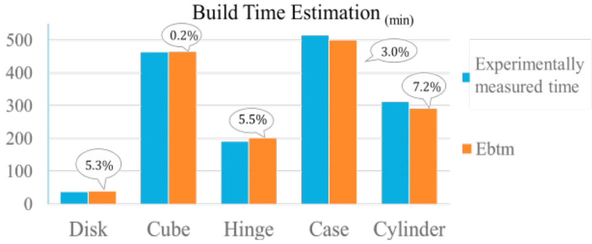

Figure 7 Empirical model results and comparison to experimental values

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