# Modeling build time, process energy consumption and cost of material jetting-based Additive Manufacturing

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## Abstract

*This paper constructs a combined build time, process energy consumption and cost estimator for an Additive Manufacturing platform of the material jetting type (Stratasys Objet Connex 260). Unlike previous estimation approaches, this paper develops a model of build time that reflects the movement of a print head depositing material in the build process. In a series of validation experiments, this approach produced accurate build time estimates in the majority of cases. The observed absolute errors range from 4.00% to 39.18% for build time estimation and from 2.58% to 48.28% for process energy consumption, exhibiting an overall mean absolute error of 15.31%. The proposed build time estimator is compared to two more general specifications, one treating deposition time per layer as fixed and one relating total build time to deposition area per layer. It is shown that both alternative specifications produce greater estimation errors.*

## Introduction

Additive Manufacturing (AM) technology is experiencing significant technology diffusion, which is illustrated by currently high industry growth rates of approximately 35% annually [1]. Underlying such industry growth are technology adoption decisions in which the costs and benefits of taking up a new technology are weighed against each other (see, for example [2]). It is therefore necessary to develop accurate and up to date models of the economic performance of AM process variants.

Taking a detailed-analysis approach to process modelling (see, for example [3]) and building on previous research by the authors [4], the goal of this paper is to develop an accurate model combining build time, process energy consumption and cost aspects for a jetting-based multi material AM platform, the Objet Connex 260 [5].

The operating principle of the Objet Connex 260 system and its main components are illustrated in Figure 1. Within an enclosed build volume, shown here with its cover open, droplets of a photoreactive monomer resin are deposited by a print head (a) onto a build platform (b). Moving in the in the X/Y plane, the print head also incorporates a UV light source to initialize a polymerization reaction and a planarization mechanism to remove excess material. After finishing the deposition of material and UV exposure within a layer, the build platform indexes down by one increment in the Z direction and the deposition process for the next layer begins. Fresh build material is fed to the jetting head from multiple material cartridges (c), each one may contain a different build material. An additional material required for the deposition of sacrificial structures connecting parts to the build plate and to support overhangs is supplied from support material cartridges (d). The excess material removed during the build process by planarization is transferred into a waste container (e).

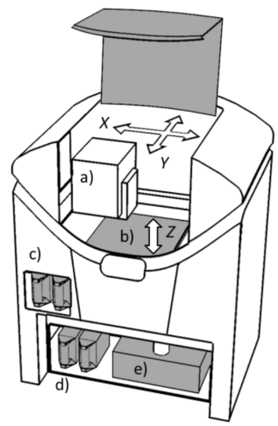


*Figure 1. Main components of a material jetting system*

This layer-by-layer build cycle is repeated until the build operation is complete and the platform (b) can be removed by the machine operator. For additional details on the operating principle of such material jetting processes, see [6]. Table 1 summarizes important characteristics of the investigated AM system.

**Table 1: Characteristics of the investigated AM system**

| | |
|---|---|
| Manufacturer and model | Stratasys Objet Connex 260 |
| Deposition type | Material jetting / printing of photopolymers |
| Nominal build volume size (X / Y / Z) | 260 × 260 × 200 mm |
| Usable platform area (X / Y) | 250 × 250 mm |
| Process atmosphere | Normal ambient |
| Primary (structural) build material | VeroClear RGD810 |
| Secondary (functional) build material | TangoBlack FLX973 |
| Support material | FullCure SUP705 |
| Manufacturer reference | Stratasys Inc. [5] |

The next section of this paper introduces the methodology employed to specify a group of build time, process energy consumption and cost estimators, presents the data sources for parameter estimation and outlines the used validation approach. The subsequent section summarizes and discusses the results of the data collection effort, estimation of model parameters and the outcome of model validation. Conclusions are drawn in the final section of this paper.

## Methodology

The process model developed for this paper is based on an existing general purpose framework combining an automated build volume packing technique with build time estimation (described in detail by [7]). This forms a suitable approach to the research objective as process time estimators provide a suitable basis for AM production cost models [8, 9, 10] and some AM processes operate efficiently only if the available capacity is fully utilized [11].

This framework utilizes a C++ implementation discretizing the problem of handling irregular and continuous geometries by using volumetric pixel, or voxel, approximations of part geometry, as proposed by [12]. To keep the implementation relatively concise, a number of simplifications are made. These include:

- using a low voxel resolution $r$ (5 mm) for faster computation and easier hard-coding of part geometries in voxel form,
- constraining part rotation to discrete 90 º increments around the Z axis to avoid undesirable material properties due to anisotropy and the avoid re-discretization of geometries,
- merging both part geometry and support structures into voxel approximations,
- non-distinction between the deposition of different photopolymers via the material jetting process,
- ignoring difficult-to-measure aspects such as build preparation and machine cleaning.

To have a baseline for the assessment of estimator performance, this paper first introduces a very simple parametric build time model. By treating total build time $T_{Build}$ as proportional to the total number of layers $l$, the time $\alpha_1$ consumed for the completion of each layer can be treated as fixed [3]. The interpretation is that build time is entirely driven by $\alpha_1$, the (vertical) Z-height of the build in the form of $l$ and any fixed (job-dependent) time consumption $T_{Job}$, for example machine warm up. Thus, this specification can be expressed:

$$T_{Build} = T_{Job} + \alpha_1 l \tag{1}$$

It is possible to refine this approach by incorporating discretized geometric information into the model via a three dimensional $x \times y \times z$ element array $\mathbf{V}$, representing voxel space. Thus, a triple $\Sigma$ operator expressing the summation of the time needed to process each voxel and a parameter of processing rate $\beta_m$ can be added to the fixed time increments $\alpha_m l$ and $T_{Job}$ for a more detailed build time estimator:

$$T_{Build} = T_{Job} + \alpha_m l + \sum_{z=1}^{Z} \sum_{y=1}^{Y} \sum_{x=1}^{X} \beta_m v_{xyz} \tag{2}$$

As previous research has applied this approach to powder bed fusion processes with good results [7] and to the Objet Connex 260 multi-material jetting platform with mixed results [4], this research does re-estimate this model.

### *Developing a new estimator*

The motivation behind this paper is the realization that for material jetting platforms, in which material is not deposited point-by-point but rather in a sweeping line (the print head (a) in Figure 1), a methodology relating processing time to part volume and geometry, such as (2), may not be ideal. The basic intuition is that material jetting is characterized by one or more discrete movements, or 'passes', of the print head in the X dimension. If the printing substrate is wider than the print head, as in the investigated AM system, it is also necessary to model the number of required passes $y^*$ (where $y^* \in \mathbb{N}$). This can be done using the least integer function, effectively splitting up the build volume into $y^*$ discrete strips oriented parallel to the X dimension. For simplicity, this paper ignores print head offsetting and interlacing and simply assumes a fixed width $w$ for each print head pass in the X direction of 50 mm. The least integer function $f$ can thus be expressed as:

$$f(y) = y^* \;\; if \;\; (y^* - 1)w < y \leq y^* w \tag{3}$$

The next step is to model the distance of print head travel relative to the substrate in the X dimension. As the print head in the analyzed Objet Connex 260 system does not exhaust its entire movement range if not required, this can be determined by identifying a set of voxels demarcating extreme points of geometry with respect to print head movement. It is important to note that the print head assembly, referred to by the manufacturer as a "print block" incorporating planarizer and UV lamps, will need to move over any deposited material its entirety. This implies that a fixed increment (measured at 320 mm) must be added to all distances travelled in the X dimension.

Combining this with the Y movement of the print head (3) requires the identification of one such voxel must for each the of the $y^*$ print head passes and at each particular Z height. This information is usefully recorded in a in a two-dimensional $y^* \times z$ element matrix $\mathbf{X}$, with each element $x_{y^*z}$ describing the maximum value observed for the voxel's first index in $\mathbf{V}$ (its location in the X dimension), given the other indexes $z$ and $y$.

This final step in the construction of the build time model is the definition of a term describing the total time needed for print head movement in various directions. Initially, this term needs to reflect the total number of layers deposited, which is done by summation of each layer corresponding to the z elements of the above defined matrix $\mathbf{X}$ and applying a metric of voxel resolution (voxel size $r$ divided by layer thickness $lt$).

For each horizontal layer of voxels, build time can be modeled by summing three elements: firstly, layer-dependent fixed time increments represented by $\alpha_2$, including aspects such as recurring movement of the print head back to its starting position and vertical platform indexing. The second element is the movement of the print head in the X orientation which, as described above, is determined by print head travel distance. Using a parameter $\beta_1$, this can be modeled by summing up the total travel time of the print head in this direction, again using the voxel resolution $r$. As a fixed time increment must be expected for each pass of the print head, this sum incorporates and additional parameter $\beta_2$. Thirdly, the term reflects the time needed for the $y^*$ moves of the print head in the Y dimension. This aspect is reflected in the model by parameter $\beta_3$. Of course, just as in the simple specification with fixed layer time (1), the build time model also includes a fixed build time element $T_{Job}$.

The build time estimator based on print head movement can thus be written as follows:

$$T_{Build} = T_{Job} + \frac{r}{lt}\sum_{i=1}^{Z}\left(\alpha_2 + \sum_{j=1}^{Y^*_z}\left(\beta_1 x_{y^*z} r + \beta_2\right) + \beta_3 y^*_{\ z}\right) \quad (4)$$

The build time model can now be combined with simple models of process energy consumption and manufacturing cost. Previous work on the energy consumption of the Objet Connex 260 platform [4] has shown that process energy consumption can be modeled accurately by focusing on build time. Therefore, this paper estimates the total energy used by the build operation, $E_{Build}$, simply by adding the energy consumed to start the system up ($E_{Job}$) to the time dependent element of energy consumption, which is obtained by multiplying the process energy consumption rate $\dot{E}_{Process}$ by the build time estimate $T_{Build}$:

$$E_{Build} = E_{Job} + \left(\dot{E}_{Process} \cdot T_{Build}\right) \quad (5)$$

The remaining element of this combined model is the specification of a cost estimator. The total cost of the build $C_{Build}$ employs the estimators of build time ($T_{Build}$) and total energy consumption ($E_{Build}$). $C_{Build}$ is thus obtained by adding the total time-dependent indirect costs, obtained by multiplying an indirect cost rate $\dot{C}_{Indirect}$ with $T_{Build}$, and adding estimates of direct cost contributions in terms of raw material and energy. The costs incurred for the three raw materials deposited by the system can be obtained by forming the dot product between a three element vector of used material volume *m* and a three element vector of raw material prices *p*. Material wastage occurring due to the planarization device built into the print head is accounted for by a uniform waste factor ω. The total energy costs are simply obtained by multiplying the energy price by the consumption estimate $E_{Build}$. Completing the combined estimator, $C_{Build}$ can be modelled as follows:

$$C_{Build} = \left(\dot{C}_{Indirect} \cdot T_{Build}\right) + \omega\left(\begin{bmatrix} m1 \\ m2 \\ m3 \end{bmatrix} \cdot \begin{bmatrix} p1 \\ p2 \\ p3 \end{bmatrix}\right) + \left(E_{Build} \cdot ep\right) \quad (6)$$

### Data collection

To collect the required data for build time parameter estimation, two experiments were performed on the Objet Connex 260. Experiment A, shown in Figure 2a, contains a small flat cuboid geometry (10 × 10 × 1 mm) located in the top right corner of the build platform and yields information on system operation when building a single small component. Experiment B, shown in Figure 2b) contains two narrow strips (5 × 250 × 1 mm) oriented in the Y direction and at both ends of the build platform. This experiment provides data on machine operation when the available build area is used up.

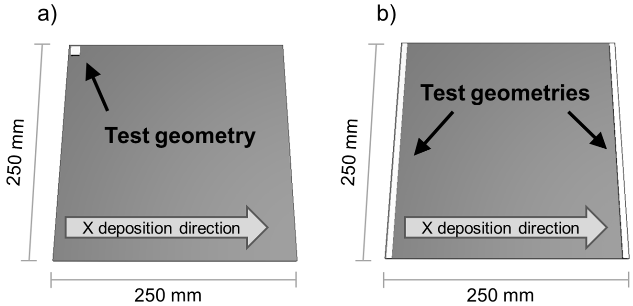


*Figure 2. Illustration of the two data collection experiments*

Both build experiments were recorded as digital video clips with a framerate of 50 frames per second. The video footage for each experiment was interrogated manually using the free video editing tool Avidemux v.2.6.10, analyzing the deposition of 20 consecutive layers during the both build experiments.

The data used in the construction of the energy consumption estimator (5) and cost model (6) are obtained from previous research and outside sources, as summarized below.

### Experimental validation

As build time and process energy consumption are measurable quantities, the accuracy of the estimated model can be assessed by calculating build time and energy consumption estimates using (4) and (5) for particular build configurations and confronting these estimates with experimental measurements for the same build configurations.

Therefore, a series of four build experiments was performed using representative test geometries from a collection of multi-material components, as shown in Figure 3. This includes a bearing block with embedded structures resembling conductive tracks (Figure 3a), a belt link component with an internal structure approximating RFID functionality (Figure 3b), and a small end cap with embedded identification markings (Figure 3c).

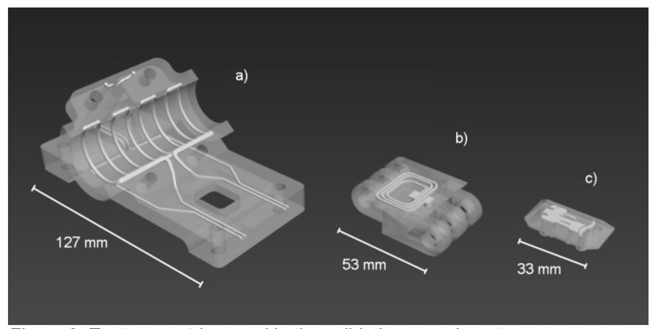


*Figure 3. Test geometries used in the validation experiments*

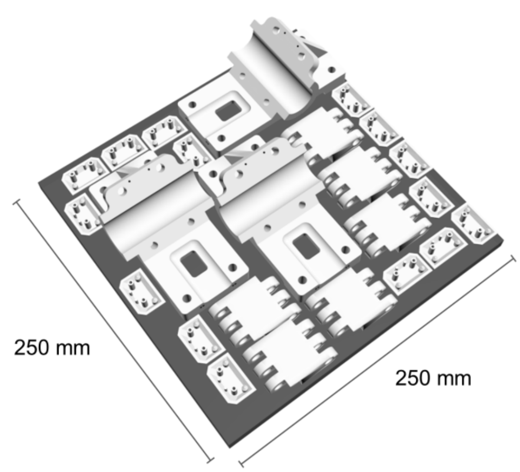


*Figure 4. Full build configuration in the first validation experiment*

In the first validation experiment, the Objet Connex 260 was operated at full capacity. To ensure this, a full build experiment was specified using a computational packing approach inserting multiple instances of the test parts shown in Figure 3. The resulting configuration, containing 3 bearing block components, 6 belt links, and 15 end caps, is shown in Figure 4.

The remaining three validation experiments are single part builds, each containing one of the three test geometries shown in Figure 3. All four validation experiments were monitored using the digital Yokogawa CW240 power meter, logging information on build duration and real power consumption with a time resolution of 1s.

## Results and discussion

### *Data collection results*

This section first presents a summary of the information obtained during the two performed data collection experiments. As can be seen in Table 2, Experiment A required a much smaller number of discrete printhead movements per layer than Experiment B (1 versus 5). The smaller movement distance during this experiment also resulted in a shorter mean movement times for the print head (5.40 s versus 7.14 s). It should be noted that the analyzed layer deposition activity in Experiment B included a nozzle cleaning operation, which allowed the calculation of a fractional time increment for inclusion in parameter $\alpha_2$, as described below.

**Table 2: Summary detailed process data collected**

| Data point / metric | Exp. A | Exp. B |
|---|---|---|
| Consecutive layers analyzed (=n) | 20 | 20 |
| Maximum X dispersion | 10 mm | 250 mm |
| Maximum Y dispersion | 10 mm | 250 mm |
| X passes, Y movements per layer | 1, 1 | 5, 5 |
| Mean duration, X passes | 5.40 s | 7.14 s |
| Standard deviation, X passes | -0.12 | 0.06 |
| Mean duration, Y movements | 0.94 s | 1.89 s |
| Standard deviation, Y movements | 0.23 | 0.68* |
| Fractional nozzle cleaning time attributable per layer | - | 0.51 s |

*omitting nozzle cleaning activity

Beyond the data collected directly from build experiments to estimate the relevant build time parameters ($\alpha_1$, $\alpha_2$, $\beta_1$, $\beta_2$ and $\beta_3$), this paper draws on a set of machine and cost parameters assembled in previous research [4].

Table 3 reports the values of the full set of additional machine and cost variables employed by the model, citing original data sources.

**Table 3: Additional model variables, adapted from [4]**

| Variable / parameter | Value | Data Source |
|---|---|---|
| Layer thickness (*lt*) | 30 μm | [5] |
| Voxel resolution *r* | 5 mm | - |
| Machine start-up ($T_{Job}$) | 254 s | [4] |
| Fixed energy usage per job ($E_{Job}$) | 0.10 MJ | [4] |
| Energy consumption rate ($\dot{E}_{Process}$) | 533.1 J/s | [4] |
| Indirect cost rate ($\dot{C}_{Indirect}$) | 26.01 $/h* | [4] |
| Material cost, VeroClear (*p1*) | 419.90 $/kg* | [13] |
| Material cost, TangoBlack (*p2*) | 419.40 $/kg | [13] |
| Material cost, Support (*p3*) | 142.02 $/kg* | [13] |
| Waste factor ($\omega$) | 1.76 | [4] |
| Energy price (*ep*) | 0.031 $/MJ* | [7] |

*estimated using a $/£ exchange rate of 1.71

### *Estimation of model parameters*

The information obtained in the data collection experiments was used to estimate the main build time parameters $\alpha_1$, $\alpha_2$, $\beta_1$, $\beta_2$ and $\beta_3$.

Parameter $\alpha_1$, needed for the simple fixed layer time estimator (1), was obtained by simply calculating the mean of all 40 build layers analyzed in the data collection experiments. This approach yielded a mean layer processing time of 25.75 s, marked by a large standard deviation of 19.71. This indicates that fixed layer time models depend to a large extent on the build configurations used for estimation.

The build time parameters needed for the print head movement time estimator (4) were estimated via two ordinary least squares (OLS) regressions, each yielding a slope term ($\beta_1$, $\beta_3$) and an intercept term ($\alpha_2$, $\beta_2$). Table 4 describes the specifications of these regressions and cites the resulting $R^2$ values, which both indicate a high degree of fit (0.99 and 0.97). It should be noted that the employed approach implicitly assumes that the underlying relationship governing build time are linear.

 

**Table 4: Parameters, estimates and goodness of fit**

| Model | Param. | Description | Estimation technique | Result | Goodness of fit |
|---|---|---|---|---|---|
| Fixed layer time estimator | $\alpha_1$ | Fixed time increment per layer | Mean of layer completion time, all data points (n=40) | 25.75 | σ = 19.71 |
| Print head movement time estimator | $\alpha_2$ | Fixed time increment per layer, includes fixed increment for Y movement and simultaneous platform indexing | Sum of fractional nozzle cleaning time (0.507 s, see Table 2) and intercept parameter of OLS regression of discrete number of Y movements (*y**) on final X pass duration per layer | 0.8936 | $R^2$=0.97 |
| | $\beta_1$ | X pass print head movement time (X dispersion related) | OLS regression of X pass duration on X pass travel distance, slope parameter | 0.0018 | $R^2$=0.99 |
| | $\beta_2$ | Fixed time increment per X pass | OLS regression of X pass duration on X pass travel distance, intercept parameter | 3.0005 | $R^2$=0.99 |
| | $\beta_3$ | Y dispersion related print head Y movement time | Sum of mean of non-final Y movement time and the slope parameter of OLS regression of discrete number of Y movements (*y**) on final X pass duration per layer | 2.0010 | $R^2$=0.97 |

**Table 5: Estimator accuracy against experimental data**

| Build configuration | | Build result | Print head movement time estimator | | Fixed layer time estimator | | Deposition area estimator [4] | |
|---|---|---|---|---|---|---|---|---|
| | | | Result | Error | Result | Error | Result | Error |
| Full build (24 parts) | Total build time ($T_{Build}$) | 1206.85 min | 1278.78 min | 5.96% | 790.90 min | -34.47% | 1406.85 min | 14.18% |
| | Total energy consumption ($E_{Build}$) | 37.79 MJ | 41.00 MJ | 8.50% | 25.40 MJ | -32.79% | 44.95 | 18.93% |
| Bearing block | Total build time ($T_{Build}$) | 380.67 min | 395.91 min | 4.00% | 790.90 min | 107.76% | - | - |
| | Total energy consumption ($E_{Build}$) | 11.95 MJ | 12.76 MJ | 6.81% | 25.40 MJ | 112.53% | - | - |
| Belt link | Total build time ($T_{Build}$) | 96.72 min | 89.77 min | -7.19% | 290.29 min | 200.14% | - | - |
| | Total energy consumption ($E_{Build}$) | 3.05 MJ | 2.97 MJ | -2.58% | 9.39 MJ | 207.71% | - | - |
| End cap | Total build time ($T_{Build}$) | 48.05 min | 66.88 min | 39.18% | 218.78 min | 355.31% | - | - |
| | Total energy consumption ($E_{Build}$) | 1.51 MJ | 2.24 MJ | 48.28% | 7.10 MJ | 370.05% | - | - |

### *Validation of model performance*

Table 5 summarizes the build time and energy consumption results from the four validation experiments and confronts them with estimates generated by the print head movement time estimator (4) and the fixed layer time estimator (1) specified for this paper. To add context, Table 5 also provides the result of a previous validation effort [4] for a build time estimator of the deposition area type (3).

As clearly shown, the movement distance estimator performs with a high degree of accuracy in three of four build experiments with absolute estimation errors ranging from 2.58% to 8.50%. For each validation experiment, the movement distance estimator outperforms both other estimators. In the final validation experiment, containing a single end cap geometry (shown in Figure 3c), the estimator is inaccurate with errors ranging of 39.18% for build time and 48.28% for energy consumption. The reason for this lies in an overstatement of Y movement time resulting from the difference in the estimate of parameter $\beta_3$ and the real duration of Y movement associated with the first print head pass. Overall, the calculated mean absolute estimation error is 15.31%.

The weak performance of the fixed layer time estimator, featuring absolute errors ranging from 32.79% to 370.05%, indicates that such estimators should be treated with caution if the layer completion time exhibited by an AM system is sensitive to the build geometry contained in the build, as illustrated in Figure 2.

Interestingly, the printhead movement time estimator, and with it the process energy consumption estimator based on it, also performs far better than the deposition area estimator [4], exhibiting less than half of the measurement error in the full build experiment. This is noteworthy as the estimator developed in this paper utilizes far less geometric information (only the set of voxels determining print head movement) than the deposition area estimator, which makes use of all information contained in the voxel representation of the build volume. This result needs to be viewed in the context of attempts to construct universal build time estimation techniques that are suitable for all AM technology variants, such as [3].

## Conclusions

This paper has demonstrated a viable route for the construction of build time estimators based on print head movement. Moreover, it has been shown that an approach of this kind can be combined with very simple energy consumption and cost models to produce estimators of AM resource consumption. The validation of these estimators for build time and process energy consumption indicates that they perform accurately in the majority of cases. The untypically large estimation errors in the fourth validation experiment (39.18% for build time and 48.28% for process energy) suggest that further refinement is needed for the estimation of small builds.

This work will be of relevance in attempts to establish the commercial viability of future high productivity material jetting systems aimed at manufacturing applications. As the specification of such 'detailed analysis' process models is necessarily aligned with the operating mechanisms of the actual machine [3], this work will be helpful in exploring how different process architectures affect the operating economics of such systems. As it has been shown that process energy consumption can be modelled alongside build time with relative ease, this will also provide important insight into the sustainability aspects of such future platforms.

Additionally, this work will be of interest in the study of the efficient operation of AM technology based on material jetting as it yields insight into the drivers of cost and process energy consumption for particular AM build configurations.

Despite analyzing one of few commercially available AM systems capable of depositing dissimilar materials in a single process, this paper has not emphasized the multi-material aspect in build time modelling (except in the cost model). This would provide an interesting are for further study.

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