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$$T_{Build} = T_{Job} + (T_{Layer} \times l) + \sum_{z=1}^{z}\sum_{y=1}^{y}\sum_{x=1}^{x} T_{Voxel\,xyz} \tag{2}$$

No allowance is made for build preparation and machine cleaning. It is felt that the time spent on these activities is difficult to measure and very much at the discretion of the machine operator. It could be argued that these activities take place during the non-operational hours.

Total energy investment, E_{Build}, can be modeled similarly to equation (2). However, a purely time-dependent element of power consumption must be expected in the continuous operation of the AM machine. This is denoted by the energy consumption rate $\dot{E}_{Time}$ (measured in MJ/s), which is multiplied by T_{Build} to estimate total time-dependent energy consumption. Modelling $\dot{E}_{Time}$ as a constant reflects the mean baseline level of energy consumption throughout the build, originating from continuously operating machine components such as cooling fans, pumps, and the control system.

E_{Job} contains all energy consumption attributable to the build job, including energy consumed by the wire erosion process to harvest the parts from the build plate. Analogous to build time estimation, E_{Layer} denotes fixed elements of energy consumption per build and layer, for a total number of layers, l. Further, the geometry-dependent energy consumption is obtained by adding all energy consumption associated with actual material deposition, $E_{Voxel\,xyz}$, throughout the discretized workspace. Please note that $E_{Voxel\,xyz}$ does not contain time-dependent power consumption. The empirical data on $E_{Voxel\,xyz}$ were obtained by monitoring machine energy consumption during the scanning process and then subtracting the energy associated with the energy consumption rate $\dot{E}_{Time}$, ensuring that this element of energy consumption is not counted twice. Thus, E_{Build} can be modeled as follows:

$$E_{Build} = E_{Job} + (\dot{E}_{Time} \times T_{Build}) + (E_{Layer} \times l) + \sum_{z=1}^{z}\sum_{y=1}^{y}\sum_{x=1}^{x} E_{Voxel\,xyz} \tag{3}$$

This energy consumption model should not be interpreted as showing how total AM energy consumption can be attributed to individual subunits of the EOSINT M270 platform. The specification was chosen with the goal of implementing a voxel-based energy consumption estimator. Moreover, both the time and energy estimators possess additional information on the real Z-height of the parts contained in the build. This is done to avoid large estimation errors arising from the inclusion of empty layers.

After developing the build time and energy consumption techniques, the next step towards the combined estimator is the construction of an activity-based cost (ABC) estimator of the type devised by Ruffo et al. (2006b). The cost estimate for the build, C_{Build}, is computed from data on the total indirect costs and direct costs incurred. All data used in the costing model are summarized in Table 1. The current research estimates the total indirect cost rate of operating the EOSINT M270 at £26.64 per hour. It is noteworthy that the system incorporates an N_2 generator, hence no protective gas from external sources is needed.

Table 1: Cost model elements (adapted from Ruffo et al. 2006b)

Production overhead			**Utilization**		
Rent, building area cost	4.53	£ / h	Utilization rate	57.04	%
			Annual machine operating hours	5000.00	h
Administration overhead					
Hardware purchase	1670.27	£	**Equipment**		
Software purchase	1670.27	£	AM equipment and wire eroder	8.00	years
Hardware cost/year	334.05	£	Hardware and software	5.00	years
Software cost/year	334.05	£			
Consumables per year	1113.52	£	**Machine costs**		
Total administration overhead	0.31	£ / h	Machine purchase	364406.80	£
			Machine purchase cost per year	45550.85	£
Production labor			Maintenance cost per year	22033.90	£
Technician annual salary	25165.45	£	Machine consumables per year	2542.37	£
Employer contributions	22.00	%	Wire erosion machine purchase	55000.00	£
Total production labor	6.14	£ / h	Total wire erosion costs per year	8165.00	£
			Total machine costs per year	78292.12	£
Total indirect cost per machine hour	**26.64**	**£**			
Direct cost for 17-4 PH powder / kg	**78.81**	**£**	**Total machine costs**	**15.66**	**£ / h**
Direct electricity cost / MJ	**0.018**	**£**			

- December 2010 mean $/£ exchange rate: 1.56

In the proposed model, two direct costs enter the total cost estimate: raw material costs and energy costs. Total raw material costs are calculated by multiplying the total mass *w* of all parts included in the build (including support structures) with the price per kilogram of the stainless steel 17-4 PH powder, $Price_{Raw\ material}$ (78.81 £/kg). Thus, any raw material losses are ignored. The expenditure for energy enters the model by multiplication of the energy consumption estimate, E_{Build}, with the mean price of electricity for the manufacturing sector in the UK, $Price_{Energy}$, currently around 0.018 £/MJ (according to DECC, 2010). The total cost estimate for the build, C_{Build}, can be expressed as:

$$C_{Build} = \left(\dot{C}_{Indirect} \times T_{Build}\right) + \left(w \times Price_{Raw\ material}\right) + \left(E_{Build} \times Price_{Energy}\right) \quad (4)$$

Results and Discussion

A full-capacity build experiment is configured by executing the build volume packing algorithm. The resulting full build configuration is shown in Figure 4. Of the available 2,025 build volume floor voxels, 92.6% were occupied. A total of 85 parts were inserted, utilizing 19.78% of the used build volume cuboid (225 mm x 225 mm x 52 mm). This value includes the auxiliary structures needed to anchor the overhanging part geometry on the substrate.

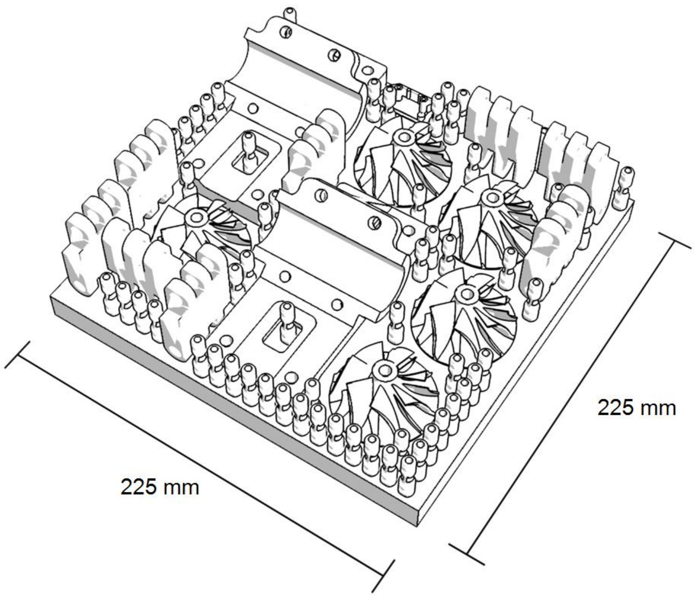

Figure 4: Full build configuration of basket parts

The full build experiment (including the wire erosion process) consumed a total of 1059.56 MJ of energy. Using the cost model specified in equation (4), C_{Build} is estimated at £3,218.87. Individual part cost and energy usage are identified through their share of total product mass (4.167 kg). A summary of the parts produced in the full build and estimates of energy usage and production cost are presented in Figure 5:

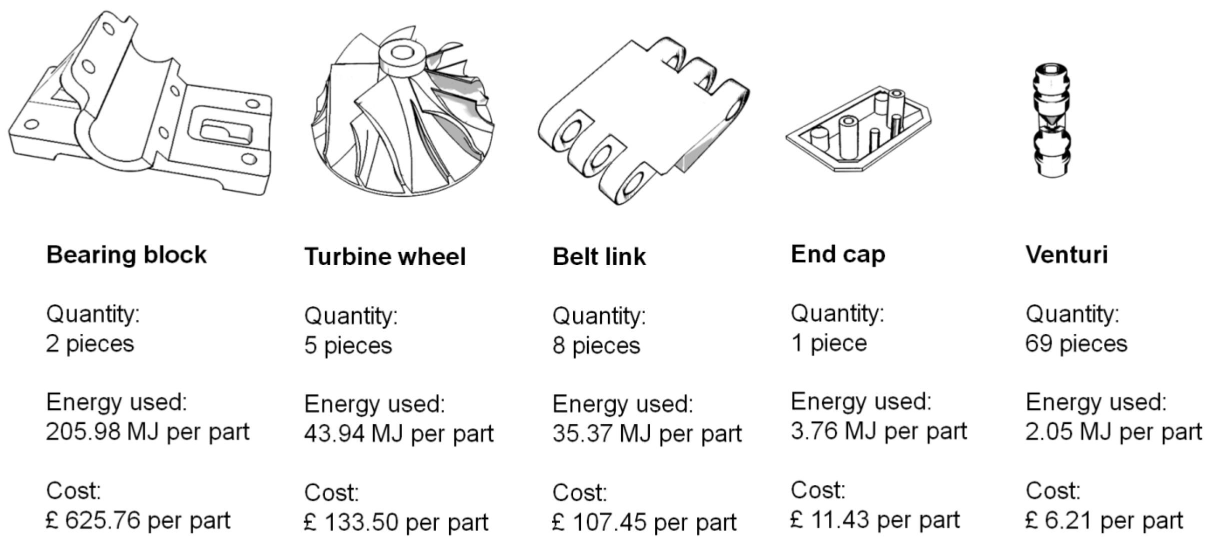

Figure 5: Estimates of energy consumption and production cost per part

The final specifications of the time and energy estimators, equations (2) and (3), are obtained from a least squares regression of the time and energy consumption data recorded during the experiment containing the layered power monitoring test part, as shown in Figure 3.

The obtained parameters α_{Time} (10.82 s) and α_{Energy} (0.008 MJ) are multiplied by the number of layers in the build l in order to obtain layer dependent time and energy consumption. The parameters expressing the time and energy attributable to the scanning of 1

mm^2 during the build, β_{Time} (0.0125 s) and β_{Energy} (0.000013 MJ), are then used in conjunction with the layer thickness lt (0.02 mm) and a measure of occupancy of each voxel to calculate total time and energy consumption per voxel, $T_{Voxel\ xyz}$ and $E_{Voxel\ xyz}$. The rate of occupancy RO_i in each voxel is modeled as the ratio of the volume of part i occupying this voxel (VP_i) and the volume of the voxel approximation for part i (VA_i):

$$RO_i = \frac{VP_i}{VA_i} \tag{5}$$

Thus, for each (5 mm)³ voxel in the position xyz holding 250 (= 5 mm / lt) layers and containing part i, the build time and energy consumption can be approximated:

$$T_{Voxel\ xyz} = \beta_{Time} \times 5^2 \times \frac{5}{lt} \times RO_i \tag{6}$$

$$E_{Voxel\ xyz} = \beta_{Energy} \times 5^2 \times \frac{5}{lt} \times RO_i \tag{7}$$

This is combined with an estimated fixed time and energy consumption for machine start-up T_{Job} (63 s) and E_{Job} (142.58 MJ, including wire erosion). The start up process is very rapid on this system as no warm up is required and the build chamber is continuously flooded with N_2 during build activity. Time dependent power consumption is obtained by multiplying the base line energy consumption rate $\dot{E}_{Time}$ (0.0015 MJ per s) with T_{Build}. Thus, the estimates of T_{Build} and E_{Build} are obtained as follows:

$$T_{Build} = T_{Job} + (\alpha_{Time} \times l) + \sum_{z=1}^{z}\sum_{y=1}^{y}\sum_{x=1}^{x} T_{Voxel\ xyz} \tag{8}$$

$$E_{Build} = E_{Job} + (\dot{E}_{Time} \times T_{Build}) + \left(\alpha_{Energy} \times l\right) + \sum_{z=1}^{z}\sum_{y=1}^{y}\sum_{x=1}^{x} E_{Voxel\ xyz} \tag{9}$$

The time and energy consumption model specified in equations (8) and (9) is experimentally validated. This is done by comparing the calculated estimates to the measured time and energy consumption during the three build experiments containing parts from the representative basket (Figure 2). Validation is performed for the full build at maximum machine capacity (shown in Figure 4) and two single part builds, the bearing block and the turbine wheel.

The results of the validation experiments and the corresponding estimates of T_{Build} and E_{Build} are presented in Table 2. Note that the validation does not include the energy consumed by the ancillary wire erosion process. It should also be mentioned that some of the venturi parts had an incorrect orientation during the build, which led to build failure for the affected parts in the final stages of the full build. However, this was deemed to have had a negligible effect on the presented results.

Table 2: Confronting the estimates with experimental results

Experiment	Time consumed	Model estimate T_{Build}	Error	Energy usage	Model estimate E_{Build}	Error
Full Build experiment	388031 s	354806 s	-8.56 %	917.10 MJ	879.93 MJ	-4.05 %
Single Bearing block	93302 s	92338 s	-1.03 %	215.48 MJ	223.13 MJ	3.55 %
Single Turbine wheel	31224 s	28504 s	-8.71 %	72.73 MJ	66.80 MJ	-8.15 %

The observed errors are likely to originate from the use of an idealized test part (Figure 3) in the experiment that provided the data. Compared to other build time estimators (Campbell et al. 2008; Munguia 2009; Ruffo et al. 2006a; Wilson 2006) the errors reported in Table 2 indicate that the developed time estimation functionality performs robustly.

This research thus demonstrates that the impacts of the fixed process elements in the DMLS process, which may be job dependent (such as machine start-up) or layer dependent (such as powder re-coating), are amortized over the number of parts contained in the build. This has been previously suggested by Baumers et al (2011) for energy consumption.

The presented technique appears appropriate for additive processes as it can be used to estimate specific energy consumption and production cost for various build configurations with multiple types of parts. To test the effect of various build compositions, eight different configurations with varying degrees of capacity utilization were estimated. The results for process energy consumption range from 1.96 MJ/cm^3 to 3.61 MJ/cm^3. Assuming a material density of 7.80 g/cm^3, this corresponds to specific energy consumption ranging from 251.28 MJ/kg to 462.82 MJ/kg. This is slightly higher than reported in previous research, ranging from 241 MJ/kg to 339 MJ/kg (Baumers et al., 2011). This difference is likely to originate from the inclusion of the energy consumed by the wire erosion process. In terms of production cost, the eight build configurations led to results ranging from 5.71 £/cm^3 to 7.44 £/cm^3.

The full build configuration shown in Figure 4 resulted in the lowest estimated energy consumption and production cost on the EOSINT M270 (1.96 MJ/cm^3 and 5.71 £/cm^3). This underlines the statement made in the introduction that for cost and energy consumption metrics to reflect efficient machine operation it is important to consider full capacity utilization. The results thus show that the configuration with the highest packing density is likely to lead to the most efficient build. This points to the conclusion that the user's ability to fully utilize the available build space is an important determinant of DMLS cost and energy consumption.

Conclusions

This research demonstrates the construction of a combined estimator of build-time, energy consumption and cost for parallel additive techniques such as DMLS which reflects technically efficient machine operation. The application of this methodology shows that the cost and energy consumption of the DMLS process are determined by the user's ability to fill the available build space. Further, the proposed method can be used to estimate the production of own designs in build volumes that are populated (where necessary) with parts drawn from a representative basket.

The developed methodology has been applied to DMLS, which is a laser-based additive platform employing a powder bed. While the results are likely to be extensible to later generations of DMLS systems (such as the EOSINT M280), it is unclear whether they are applicable to other additive processes. These could be platforms operating with a powder bed (for example, Electron Beam Melting) or those with an entirely different operating principle (for example, Fused Deposition Modelling). Further research is needed in this area. Moreover, the model described in this paper is limited to so called 'well structured' costs of manufacturing (Son, 1991). Ill structured costs arising from factors such as build failure, machine idleness and inventory expenses are ignored.

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