

## MODELLING STEREOLITHOGRAPHY PROCESS PARAMETERS USING SYSTEM DYNAMICS

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### ABSTRACT

Stereolithograph is one of the most popular processes in additive manufacturing. Inefficiencies in the stereolithography process, which lead to unsatisfactory levels of quality in parts produced, are reported in literature with focus on finding the correct setting of different parameters that affect the process. Although these works studied the effect of different building strategies on part characteristics; yet, these only reported the effect of the parameters without taking into consideration the interrelationships of these parameters that is conflicting in nature. Hence, a systems approach is needed that can identify these interrelationships and enhance learning and understanding of this system of interacting parameters. System dynamics is a method to describe, model, analyze and simulate dynamically complex systems; where, in this paper, two of the system dynamics diagramming tools, the causal loop diagram and stock and flow are used. Causal loop diagram is used to capture the interactions between the stereolithography process parameters. The causes and effects of the most significant parameters are described. Stock and flow is used to visually show how variables change with time. Stock and flow, along with simple mathematical equations has enabled to simulate the behavior of the system over time. The model developed has shown to be very useful in understanding the interactions between these building parameters and how they affect the part building time efficiency.

**Keywords:** Additive manufacturing, stereolithography process, system dynamics, causal loop diagram, stock and flow

### 1 INTRODUCTION:

Additive manufacturing (AM) is a technology that is being used for more than 20 years. AM was used to build prototypes only but nowadays this technology is used to build up final products and tools. AM can make physical parts directly from a CAD model by adding layer upon layer in a matter of hours; its conceptualization is to add material rather than subtracting. Moreover, AM can build very complex parts in short time that is difficult to be produced by other conventional methods. AM is also known as layer manufacturing, rapid manufacturing, solid freeform fabrication and direct digital manufacturing [1][2].

There are many advantages of using AM technology, include new design freedom, removal of the tooling requirement, economical low volumes and potential for simpler supply chains as it shortens lead times and lowers inventories. Thus, AM has achieved a high level in some applications like aerospace, automotive, biomedical, dental restorations and jewellery [2], [3].

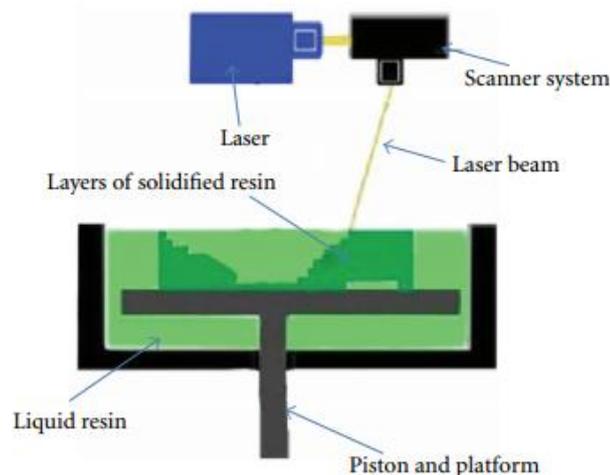
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AM is classified in to four categories according to the processing material, which are powder based such as selective laser sintering (SLS) and 3D printing, solid based such as object manufacturing, liquid based such as stereolithography (SL), and filament/paste based such as fused deposition modelling (FDM) [2].

There are some key steps in most of AM process, a 3D CAD model of the part is first prepared. The CAD file must be converted to a language that can be understandable by the machine. A Standard Triangular Language (STL) file is used, which converts the 3D CAD model in to 2D. A slicing technique is then used to slice the CAD model in to very thin layers which are equal to the building layer thickness, the file is transferred to the machine, and machine process parameters are set up. Then, part building takes place, which differs from one technology to another. After part removal from the machine, a post processing may be required according to the technology. Finally the part is ready for usage [3].

Stereolithography (SL) is one of the most popular technologies in AM and the first commercially available. It is a photopolymerization process which changes the liquid photopolymer resin in to solid by using an ultraviolet (UV) laser beam. Part building process in SL takes place on a movable platform which is positioned below the liquid resin surface as shown in Figure 1. An UV laser beam moved by a computer controlled optic scanning system across the vat which contains the liquid. The laser traces the first layer, which selectively solidifies the resin while keeping the remaining resin in its liquid state. It actually draws each layer of the part from the provided data in the building file. Afterwards, an elevator lowers the platform by a distance which is equal to the chosen layer thickness. Then, the recoater blade slides over the vat for smoothing the surface. The laser traces the next layer above the first one and each layer drawn is adhering to the one before. This process is repeated till all layers are completed and; hence, completing the part building. Finally, the platform rises up containing the completed part. The part is then removed from the platform, the supports are broken, and the final part is cleaned from any excess liquid. The part is then subjected to a post curing process in which the part is put in an oven or furnace to be fully cured. As, depending on the resin type, usually during the photopolymerization process the part does not reach 100% solidification (about 95-96% solidification is obtained during the building process) [4], [5].



**Figure 1: Stereolithography process [6].**

Compared to other AM technologies, SL has the best part build accuracy and surface finish. However; the parts produced by SL are still prone to unsatisfactory levels of quality due to process capabilities, material capabilities and incorrect building strategies. The process parameters affect the physical and mechanical properties of the parts produced and can impact the efficiency of building the part with required quality levels and in minimal time [4].

The objective of this paper is to model the SL process parameters, in order to understand the overall SL process, identify the interrelationships between the different process parameters, describe the overall effect of these parameters' settings on the part building process and simulate its behavior over time using the SD approach.

The rest of the paper is organized as follows: section 2 gives an overview of previous work reported in literature, section 3 describes the SL process parameters, section 4 presents the SD developed model, section 5 shows the simulation results, and finally section 6 is the conclusion and future work.

## 2 LITRETURE REVIEW

One of the main problems in the research field is determining the suitable process parameters that can satisfy the different quality characteristics. Many researchers focused on studying and or optimizing the building process parameters to find the most significant ones in regard to the part properties, in order to improve the part quality and predict the future properties.

Emad Rajani and Hamdi [7] have used previous work done by S H Lee [8] to investigate the influence of part parameters such as layer thickness, hatch overcure and the hatch spacing on the part accuracy. After that an artificial neural network (ANN) model was developed to relate these parameters to the part dimensional accuracy. They found out that as the layer thickness and hatch overcure increase, the dimensional error increases too; so these variables are called "positive factors". In contrast, as the hatch spacing increases, the dimensional error decreases; this variable is called "negative factor". Then, the ANN was imported to two optimization algorithm Genetic algorithm (GA) and simulated annealing (SA) to find the optimum values. They concluded that using both GA and SA methods give equal optimal values for SL parameters which are layer thickness = 0.1; hatch overcure = -0.038; hatch spacing = 0.25.

K. Chockalingam *et. al.* [5] made an attempt to identify the part and support process parameters. From the several process parameters in the SL, they found out that the orientation, post curing time and layer thickness contributes 33%, 29% and 9.4% respectively to the part strength. Then, the Design of experiment method (DOE) method was used for the optimization process which summed up to use a vertical orientation, post curing time = 60 minutes and layer thickness = 0.1 mm. Furthermore, from the DOE method an empirical regression equation was established to predict the relationship between these process parameters and part strength in future.

B. S. Raju *et. al.* [9] discussed the mechanical properties required for producing dies in SL machine. Since they are subjected to high compression, tension and impact factor from the high injection pressure. They studied only one single factor of the part process parameter which is the layer thickness. They tested out the influence of three different values for the layer thickness which are (50-100-150) micron on flexural property, ultimate tensile strength and impact strength. The optimum layer thickness that gave a high strength with high accuracy and good surface finish is equal to 100 microns. B. S. Raju, U. Chandrashekar and D. N. Drakshayani [10] also discussed the same issue but with different method on part and support parameters. By conducting taguchi's method, they found out the optimum layer thickness = 0.125 mm, 90 degree orientation and hatch spacing = 0.015 mm.

Other researchers have modified the SL process to enhance the quality characteristics and the efficiency of building. For example, Cao Yi, Li Ditchen and Wu Jing [11] have enhanced the machine process parameters by developing a novel SL process with a variable beam spot in a single built. The new system includes a controllable optical system and controllable software which varies the beam spot size and control it. This modification has improved the building efficiency with 30% without increasing the cost or even reducing the accuracy.

Eun-Dok Lee and Jae-Hyung Sim [12] have developed a new SL machine that uses neural network approach, which automatically determines the optimum part process parameters values to minimize the surface roughness and build time. During the experimentation, they investigated that the smaller the layer thickness is, the better the surface roughness and the longer building time. On contrary, the larger the layer thickness is, the shorter the building time, the worst surface roughness with incomplete solidification. Overall, the developed SL showed more efficient results than the traditional one.

Some researchers modelled the SL machine and part processes parameters such as Y.M. Huang and C.P. Jiang [13] for analysing the shrinkage and curl distortion during the photopolymerization process. Since parameter such as scan speed and slicing thickness lead to different shrinkage and curl distortion levels which means that the material behaviour is dynamic, a dynamic finite element method was chosen to model the SL process. After simulating the model, they found out that a short raster causes less curl distortion than a long one.

It is obvious from the review of literature that most researchers focused on studying and/or optimizing the SL process parameters; where, they addressed only one or two types of the SL process parameters. Furthermore, the interaction of the different parameters and its effect on the whole system is rarely addressed.

### 3 STEREO LITHOGRAPHY PROCESS PARAMETERS

There are many types of SL parameters which are part parameters, support parameters, recoat parameters, machine parameters, and Resin parameters. In the developed model the part parameters, machine parameters and Resin parameters are used.

E. R. Khorasani and H. Baseri [7] presented the following definitions for some of part process parameters which are shown in Figure 2:

- Layer thickness ( $l_{th}$ ): is the depth of a layer, the region that solidifies at the same elevation.
- Cure depth ( $C_d$ ): is the depth of the strand.
- Hatch Spacing ( $h_s$ ): is the distance between the centerlines of adjacent parallel hatch strands or is the distance between two successful movement of laser.
- Overcure ( $O_c$ ): is the depth of a strand pierces in to the lower adjacent layer. If it is located at the lateral boundaries it is called "boarder overcure ( $b_o$ )"; otherwise "Hatch overcure ( $h_o$ )".

Some of the machine parameters are listed in [14],[15].

- Beam radius ( $w_o$ ): is the radius of laser beam focused on the resin
- Laser power ( $L_p$ ): the power of the laser beam.
- Maximum exposure ( $E_{max}$ ) = peak exposure of laser shining on the resin surface (center of laser spot).

The material parameters are:

- Critical Exposure ( $E_c$ ): is the exposure in which resin solidification starts to occur.
- Depth penetration ( $D_p$ ): is the depth of penetration of laser into a resin until a reduction in irradiance of  $1/e$  is reached.

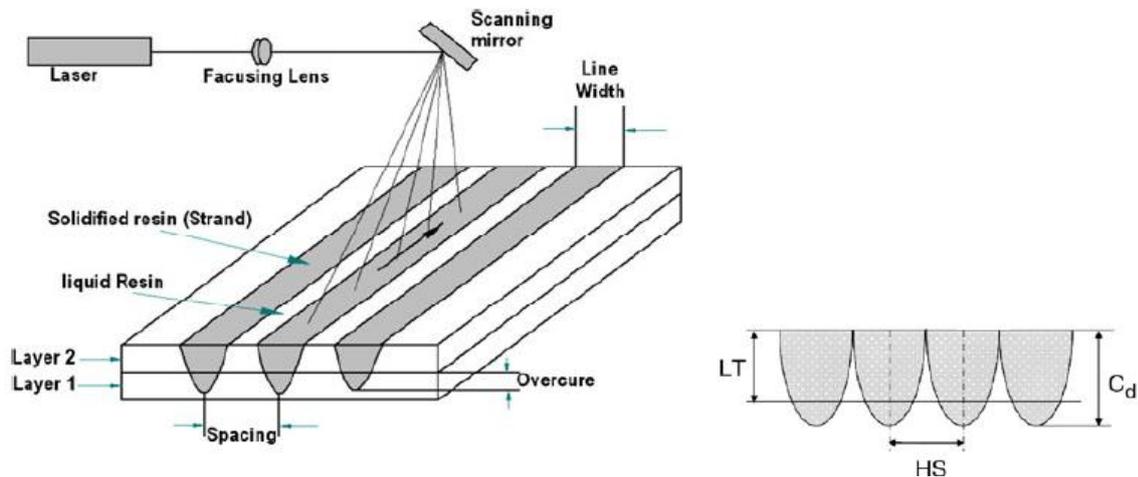


Figure 2: Process parameters in stereolithography [10].

As mentioned earlier this paper aims to fill the research gap identified in the previous section by modelling three types of SL process parameters simultaneously; which are the part, machine, and resin parameters. A system dynamics (SD) approach is employed to model the SL process by developing causal loop diagram (CLD) and stock and flow diagrams. The developed model is intended to show the interrelationships of three types of the building parameters and the overall effect of each parameter on the part building process. Model development is discussed in details in the following section.

#### 4 MODEL DEVELOPMENT

The SD as a modelling technique is different from other available techniques in that instead of looking for isolated events and their causes in a system; it uses a systems approach that provides an overall view of that system. Furthermore, SD allows using feedback loops, time delays, and stock and flow which are essential for representing the dynamic nature of any system. Hence, SD helps in visualizing the system structure, understanding, modelling, analysing, and simulating the system behaviour in terms of graphs over time. SD has been used in many areas such as supply chain management [16], healthcare [17] and logistic outsourcing [18] with few evidence of applications in the field of manufacturing processes. That's why in this paper system dynamics (SD) is used as a modelling approach to model the complex and dynamic process of stereolithography.

The "Vensim" software has been used as a modelling and simulation environment for developing the SL process model shown in Figure 3. The CLD maps the causal links among the different variables with an arrow from the cause to the effect. Causal link is assigned a polarity, either positive (+) or negative (-) to indicate how the dependent variable changes when the independent variable changes. Link polarities describe the structure of the system, they do not describe the behaviour of the variables [19].

For example, a "positive polarity" linking  $C_d$  and  $E_{max}$  means that when the  $C_d$  increases (*decreases*), the  $E_{max}$  increases *above* (*decreases below*) what it would otherwise have been; while a "negative polarity" between  $D_p$  and  $E_{max}$  means that when  $D_p$  increases (*decreases*),  $E_{max}$  decreases *below* (*increases above*) what it would otherwise have been.

CLD also represent the feedback loops of the system. As shown in Figure 4, the B in the center of the loop denotes a balancing feedback loop. When the Gap decrease, both the building exposure rate and actual exposure decrease; then the actual exposure makes the Gap to increase. This loop makes the system at a stable condition as the gap decreases at the beginning; the actual exposure makes the Gap to increase at the end.

On the other hand, stock and flow diagram represents the variables that change over time. It is used to capture the stock and flow in the SL process. As shown in the figure, an example

of a stock in the model is the Actual Exposure, in which the amount of stock changes over time through the inflow rate and outflow rate; these are the exposure building rate and the rate of decay, respectively.

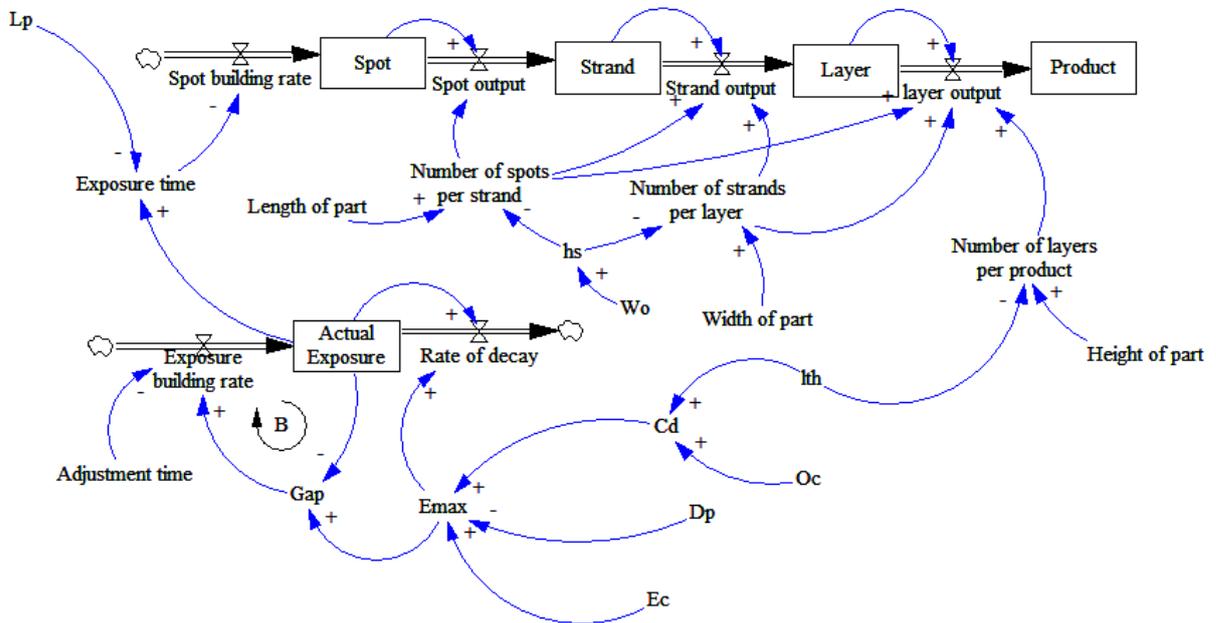


Figure 3: The model of SL process using “Vensim”.

The model developed here is composed of two main parts; the first part is the laser exposure shown in Figure 4, while the second is the building process shown in Figure 5. Each of them is bounded by a source and sinks shape.

Part 1: Laser Exposure

Figure 4 models the exposure energy which is needed to build up the stereolithography parts. As the desired cure depth specified, the system starts to adjust the exposure energy to reach its maximum value in order to exceed the  $E_c$  to obtain full solidification. There is always a Gap between the actual exposure and the desired exposure due to the rate of decay that may happen during the exposure building process. This decay is actually because of the movement of the laser beam from spot to another along a strand.

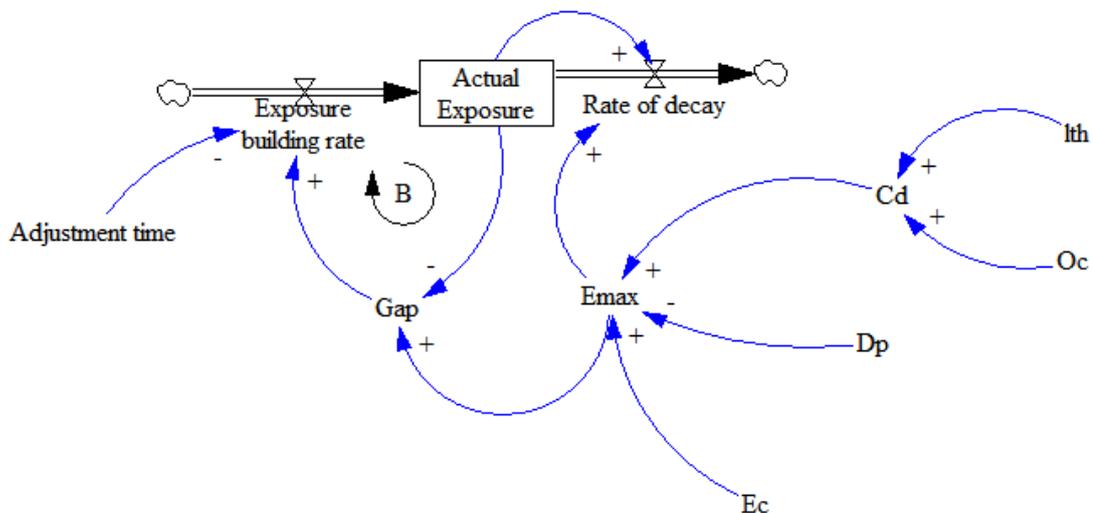


Figure 4: Laser exposure.

According to J. G. Zhou, D. Herscovici, and C. C. Chen [20] the desired cure depth is equal to:

$$C_d = l_{th} + O_c \tag{1}$$

In order to be sure that the part is cured, the maximum exposure must exceed the resin critical exposure. Both  $E_c$  and  $D_p$  are resin characteristics.

$$E_{max} = E_c * \exp \frac{C_d}{D_p} \tag{2}$$

The Gap is the difference between the Desired amount of energy needed to cure a single spot ( $E_{max}$ ) and the actual amount of energy (Actual Exposure).

$$Gap = Desired\ value - Actual\ Value \tag{3}$$

The exposure building rate is equal to the amount of energy produced per unit time. The amount of energy produced should always be at its maximum value. The unit time is the time of adjustment.

$$Exposure\ building\ rate = \frac{GAP}{Adjustment\ time} \tag{4}$$

The stock of the actual exposure is the difference between the input and the output. In which the input is the exposure building rate and the output is the rate of decay. There is a little decay that happens in the energy during the laser movement from point to another. More details can be found in P. F. Jacobs [21]

$$Actual\ Exposure = Exposure\ building\ rate - rate\ of\ decay \tag{5}$$

With initial value = 0

Part 2: Part Building Process

In the second part of the model, shown in Figure 5, the Actual exposures value is obtained from the first part of the model, in order to start the building process and the  $l_{th}$  is needed to obtain the number of layers built per product. In this model, SL process is broken down in more details; the product is treated as being composed of a group of layers, a layer is composed of a group of strands, and finally a strand is composed of a number of spots. Thus, the analysis of the building process focuses on the number of spots produced per built rather than what is reported by other researchers who base their analysis on the number of layers per built.

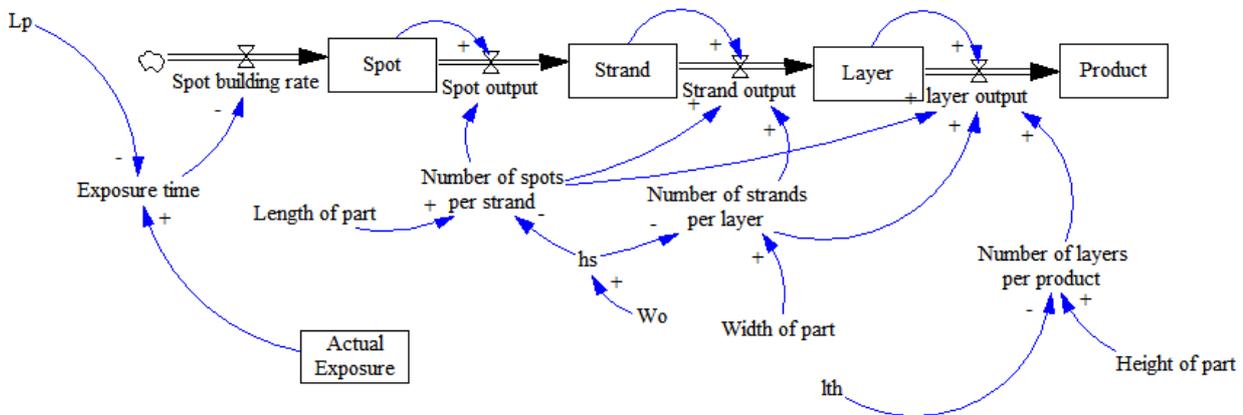


Figure 5: Part building.

In order to achieve the maximum energy, a total exposure time is needed for each spot, which is equal to the actual exposure energy divided by the laser power [20].

$$\text{Exposure time} = \frac{\text{Actual Exposure}}{\text{Laser power}} \quad (6)$$

The actual exposure needed for Equation (6) should be at its maximum value, because there is fluctuation in the exposure value. “*m*” is a constant value just to make sure to take the maximum exposure value. This constant is determined from the actual exposure maximum point on graph.

$$\text{Exposure time} = \frac{\text{MAX (Actual exposure, } m)}{\text{laserpower}} \quad (7)$$

The spot building rate is the inverse of the exposure time.

$$\text{Spot building rate} = \left( \frac{1}{\text{Exposure time}} \right) \quad (8)$$

The spot stock is the difference between the input and output flows with an initial stock value = 0. The input flow should be the maximum value of the spot building rate while the output flow is the number of spots completed per unit time.

$$\text{Spot} = \text{INTEGER} ( \text{MAX} ( \text{Spot building rate}, 0 ) ) - \text{Spot output} \quad (9)$$

The hatch spacing is calculated based on Equation (10). *K* is a constant value which varies in literature but all within the same range  $1 < K \leq 2$  [11][21].

$$HS = K * W_0 \quad (10)$$

The number of spots per a single strand is equal to the part length divided by the hatch spacing. This value should be integer value.

$$\text{Number of spots per strand} = \text{INTEGER} \left( \frac{\text{Length of part}}{h_s} \right) \quad (11)$$

The spot output depends on the number of spots in stock and the number of spots per strand needed.

$$\text{Spot Output} = \text{Spot} - \text{Number of spots per strand} \quad (12)$$

Strand stock is the difference between the number of spots completed per unit time and number of strands completed per unit time with an initial strand stock value of zero.

$$\text{Strand} = \text{Spot output} - \text{Strand output} \quad (13)$$

The number of strands per a single layer is equal to the part width divided by the hatch spacing. This value should be integer value.

$$\text{Number of strands per layer} = \text{INTEGER}(\text{Width of part}/h_s) \quad (14)$$

Strand output is equal to the number of spots needed to build a single strand.

$$\text{Strand Output} = \text{Number of spots per strand} * \text{Number of strands per layer} \quad (15)$$

The layer stock is the difference between the number of strands completed per unit time and number of layers completed per unit time with an initial layer stock value of zero.

$$\text{Layer} = \text{Strand output} - \text{layer output} \quad (16)$$

The number of layers per a single product is equal to the part height divided by the hatch spacing. This value should be integer value.

$$\text{Number of layers per product} = \text{INTEGER}(\text{Height of part}/l_{th}) \quad (17)$$

Layer output is equal to the number of spots needed to build a single product.

$$\text{Layer} = \text{number of layers per product} * \text{number strands per layer} * \text{number of spots per strand} \quad (18)$$

The stock of the product is equal to the number of layers produced per unit time with an initial product stock value of zero.

$$Product = Layer\ output \quad (19)$$

## 5 EXPERIMENTATION, RESULTS, AND ANALYSIS

### 5.1 Model Input

To test the developed model, SL 5000 is used with  $L_p = 216$  mW, Beam diameter = 0.20 - 0.30 mm,  $L_{th} = 0.15$  mm and Maximum recommended part drawing speed = 5.0 m/sec. The material used is SL7510 Resin which is commonly used with the SL 5000 with  $E_c = 10.9$  mj/cm<sup>2</sup> and  $D_p = 5.5$  mils. According to the machine and Resin specification  $O_c = 0.02$  mm (Table 1 lists all model input values). A simple rectangular box part was chosen with dimension 20mm x 10mm x 20 mm.

Table 1: Model input

$L_p$	216 mW
$W_o$	0.1 mm
$L_{th}$	0.15 mm
$O_c$	0.02 mm
$E_c$	0.109 mJ/mm <sup>2</sup>
$D_p$	0.1397 mm
<i>Length</i>	20 mm
<i>Width</i>	10 mm
<i>Height</i>	20 mm
<i>Adjustment time</i>	1 second
$M$	0.36 mJ/mm <sup>2</sup>
$K$	1.5

Once all the equations are specified, the model is simulated to analyse the behaviour of the building process over the time. The following simulation parameters were set: INITIAL TIME is zero, FINAL TIME is 5,000 and TIME STEP = 1 (all units are in seconds).

### 5.2 Results and Analysis

#### Product graph:

The graph in Figure 6 shows the output of the building process. It represents the relationship between the spots and the time taken to build the product. As seen it took about 1,622 seconds (almost half an hour) to build a single product which is equal to 1,167,474 spots. The time taken to build a product in the model is almost near to the time of SL 5000 takes to build a same size product. From this graph it can be concluded that the model succeeded to present the SL process building process.

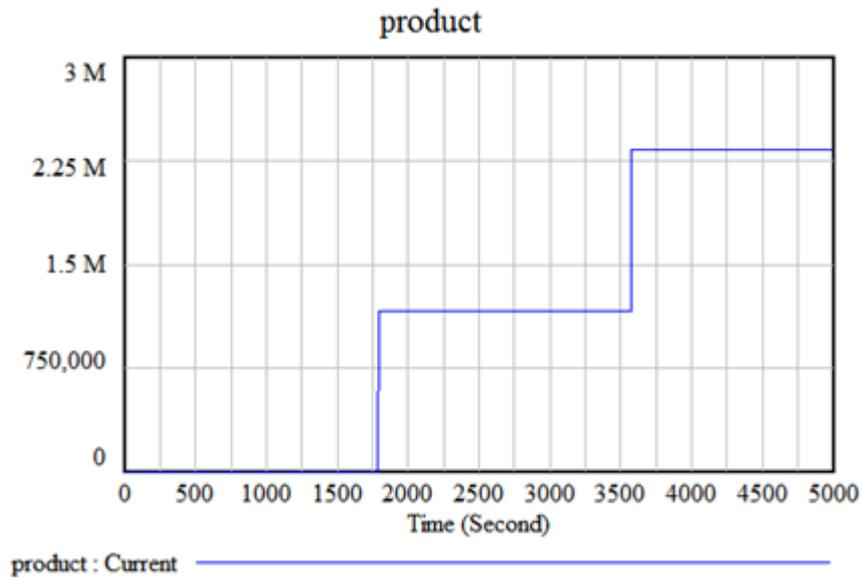


Figure 6: Output of the building process graph.

**Layers graph:**

The inclined line in Figure 7 has small stairs steps. Each step represents a single layer till building the required number of layers to produce a single product. In which each product is represented by a vertical line. This shows the layers building process till the required number of layers per product is reached and a complete product is output.

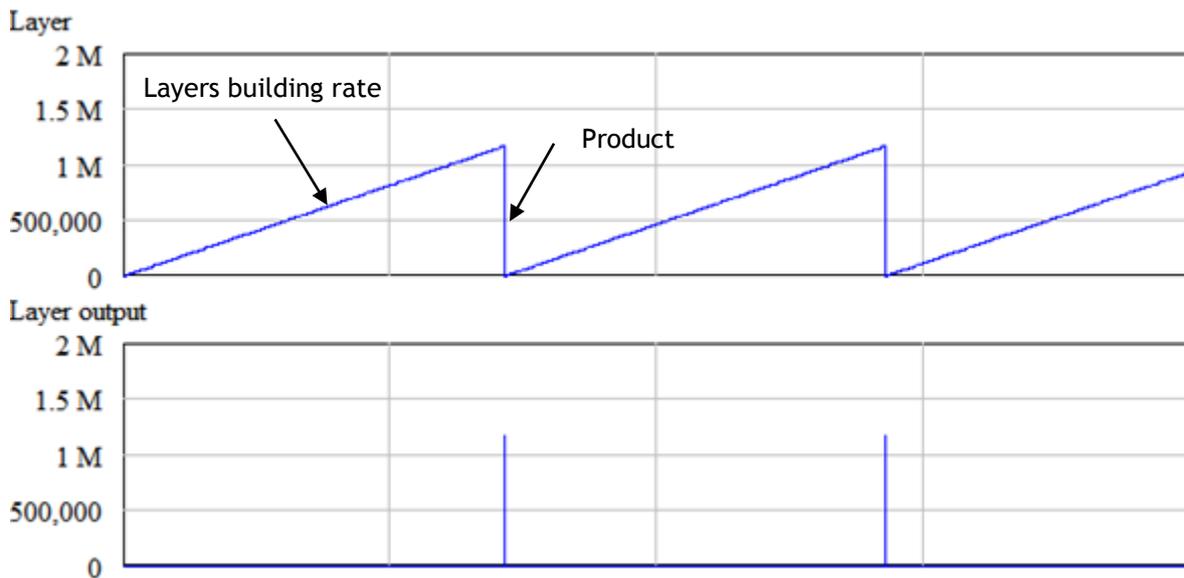


Figure 7: Layer graph

**5.3 Testing the Effect of Changing Paramters**

The effect of changing a single parameter overall the system is studied. Figure 8 shows the effect of changing the laser power from 216 mW to 160 mW. It took about 2,416 seconds (almost 40 minutes) to build a single product which is equal to 1,167,474 spots. Therefore, as the laser power decreases the part building time increases “negative polarity”.

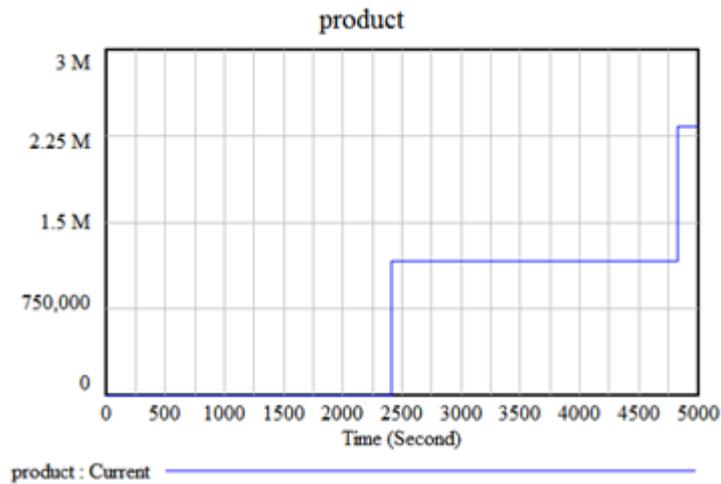


Figure 8: Effect of changing the laser power on the building process graph

## 6 CONCLUSIONS AND FUTURE WORK

In this paper, an attempt has been made to model the three types of SL process parameters which are the part, machine and resin parameters using the system dynamics approach (SD). A causal loop diagram (CLD) and stock and flow were used to model the process with some of its parameters. CLD showed the interrelationships between the variable and presented the feedback loop. On the other hand, stock and flow represented the stocks and flow of different area in the SL process. The simulation results graphically showed the number of spots over the building time efficiency. It took about 1622 seconds (27 minutes) to build a single product which is equal to 1,167,474 spots. Furthermore, simulation was done with different laser power value. The results showed that when the laser power decreases, the building time increases “negative factor”. This again confirms that the SD approach succeeded to model the SL process.

The Future work would typically include a full investigation of the effect of changing process parameters values, part size, and resin type on the part building time. Moreover, inclusion of even more SL building parameters in the model and identifying their effects on the system.

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