ARAB ACADEMY FOR SCIENCE, TECHNOLOGY, AND MARITIME TRANSPORT (AASTMT)

College of Engineering and Technology

Department of Industrial and Management Engineering

MODELLING STEREOLITHOGRAPHY PROCESS PARAMETERS USING SYSTEM DYNAMICS

By

LINA ESSAM EL-SHERIF MOHAMED

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Supervisors

Prof. Khaled S. El-Kilany
Professor of Industrial Engineering
Department of Industrial and Management Engineering

Dr. Mootaz M. Ghazy
Assistant Professor
Department of Industrial and Management Engineering

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DECLARATION

I certify that all the material in this thesis that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this thesis reflect my own personal views, and are not necessarily endorsed by the University.

Name…………………………………………………………..

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ABSTRACT

Stereolithography is one of the most popular processes in additive manufacturing technology. One of the major issues that face researchers and practitioners is the inefficiency of setting the different process parameters of the stereolithography process that affect the built parts quality and characteristics. Although researchers studied the effect of different building strategies on part characteristics; yet, they only reported the effect of the parameters without taking into consideration the interrelationships of these parameters that are mostly 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, analyse and simulate dynamically complex systems. This work has used two of the most popular system dynamics tools which are the causal loop diagrams (qualitative tool) and the stock and flow diagrams (quantitative tool). Causal loop diagrams are used to capture the interactions between the stereolithography process parameters. The causes and effects of the most significant parameters reported in literature are modelled such as laser power, exposure energy, critical exposure, depth penetration, hatch spacing, cure depth, over-cure and their effect on part dimensional accuracy, surface roughness, part completion time and tensile strength. Moreover, stock and flow diagrams are used to simulate how different variables such as the exposure energy and the part building time would change with time. The developed qualitative model has shown to be very useful in understanding the interactions between the building parameters. Whereas, the quantitative model with the introduction of the mathematical relationships between the different variables has shown the interactions between the different process parameters of stereolithography process in a measurable way and how they affect the part surface roughness and completion time. Finally, the behaviour of the system is effectively simulated over time and empirical relationships are developed between some parameters and response variables like layer thickness with the building time and surface roughness, laser power with exposure time and building time, beam spot radius with building time and surface angle with surface roughness. Modelling stereolithogtaphy by using system dynamics approach is a novel methodology used in the additive manufacturing field which has shown the relationship between different

variables with the whole system, instead of investigating the effect of specific parameters.

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LIST OF ACRONYMS/ABBREVIATIONS

AM	Additive Manufacturing
ANN	Artificial Neural Network
ANOVA	Analysis of variance
CAD	Computer Aided Design
CLD	Causal Loop Diagram
CRSC	Coefficient of resin's shrinkage compensation
CO_2	Carbon dioxide
DFE	Dynamic finite element
DOE	Design of experiments
EBM	Electron Beam Melting
FDM	Fused Deposition Modelling
GA	Genetic Algorithm
LOM	Laminated Object Manufacturing
LASER	Light Amplification by Stimulated Emission of Radiation
RFP	Rapid Freeze Prototyping
SA	Simulated Annealing
SD	System Dynamics
SL	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
S/N ratio	Signal-to-Noise ratios
STL	Standard Tessellation/ Triangular Language
UV	Ultraviolet
3 D	3 Dimensional

LIST OF NOTATIONS

Beam radius (w_o)

Critical Exposure (E_c)

Cure depth (C_d)

Depth penetration (D_p)

Hatch Spacing (h_s)

Layer thickness (l_{th})

Laser power (L_p)

Maximum exposure (E_{max})

Orientation angle (θ)

Surface angle (θ_N)

Over-cure (O_c)

Scan speed(S_v)

Chapter One

1 INTRODUCTION

Additive manufacturing (AM) is a group of emerging technologies that create objects from the bottom-up by adding material one cross-sectional layer at a time. AM offers “design freedom” for engineers, creation of functional parts without the need for assembly, and minimal use of harmful chemicals and material waste [1].

The technology has grown popular over the past 20 years, and it has been implemented by many manufacturing companies, because of its effectiveness in shortening the new products development cycle time and its ability to adapt to any rapid changes in products [2]. Hague *et. al.* [3] have mentioned that “*the use of rapid prototyping in product design and development has had a significantly positive effect and has been shown to reduce development costs by 40 to 70% and the time to market by as much as 90%*”.

With technology expansion and prices drop, AM promises more and more reduced production costs and manufacturing lead time. This means that more goods will be manufactured at or close to their point of purchase or consumption and goods will be more customized to customer needs and requirements. Although it is still doubtful that AM will advance as a replacement for mass production; yet, highly flexible, small-scale manufacturing, promises manufacturers to compete in a global environment based on customization and responsiveness [4].

AM is a process that makes physical parts directly from a three dimensional (3D) computer aided design (CAD) model by adding layer after layer. Its conceptualization relies on building the product by adding material [5]. Unlike, either **conventional manufacturing** which fabricates products by using a planned tool movement that cuts away material from a solid block to form the desired part (subtractive) or **formative processes** which use a custom designed tooling to solidify material into the desired shape. AM, on the other hand, does not require custom tooling or planned tool movement to build the final shape [4, 6, 7].

AM is very useful in producing individual, small batches and complex parts with reasonable unit cost , on the other side, conventional methods are more suitable for mass production with more stable product design [8] .

AM is a collective name for a set of different processes such as Selective Laser Sintering, Fused Deposition Modelling and 3-Dimensional Printing. One of the most popular technologies in AM technology is the Stereolithography (SL) process. SL is the first commercial AM process which is marked by 3D systems [7, 9] . In spite, SL process has the best part accuracy compared to other AM processes; the parts produced by SL are still prone to unsatisfactory levels of quality due many reasons that will be discussed in 2.4. One of these reasons, is the process parameters settings that affect the part building time and quality levels [10].

To that end, review of literature has been carried out to determine how different parameter settings affect machining accuracy, roughness, mechanical properties, and part completion time. It was evident from Literature that most researchers focus on setting some set of parameters and evaluating its effect on few responses; moreover, the interactions between these parameters and their interrelationships were rarely addressed. Thus, a detailed study is done for identifying these parameters and showing their effects on the part quality characteristics and part building time. For that, a systems approach was adopted in this work to show how the process parameters affect each other and; hence, the different responses that reflect the part building time and quality.

One of the most famous system thinking tools is the system dynamics (SD) tool. SD is usually applied in the field of supply chain and healthcare with no evidence (based on the review conducted) in the field of manufacturing technologies. SD can model a system in two different aspects; a qualitative and quantitative aspects. Through this work development of SD models for the SL process are developed to address both aspects. The qualitative model will help the SL users to see various conflicts they may face while selecting the process parameters; whereas, the quantitative model will quantitatively show how the parameters affect different responses, how the variables change with time, and how the process building time will change with the selected input parameters value. Furthermore, the quantitative model will be used to develop empirical relationships between key process parameters and responses.

1.1 AIM AND OBJECTIVES OF THE WORK

1.1.1 Aim of the Work

This work aims to model the SL building process parameters in order to address the relationships between them showing the conflicts that exists between them, and the effects of these process parameters on different responses such as part quality and part completion time.

1.1.2 Objectives of the Work

The objectives of this work include the following:

1. Defining the different SL process parameters and showing the interrelationships between them.

2. Developing a qualitative model which graphically illustrate the overall effect of the process parameters settings on the part building process time, accuracy, surface finish, and tensile strength.

3. Developing a quantitative model to investigate the effect of various parameters on the system as a whole.

4. Predicting the time taken by SL process to build up a part.

5. Developing empirical relationships between process parameters and responses.

1.2 THESIS OUTLINE

The Thesis consists of six main chapters, including the current chapter, and four appendices. The thesis is organized as follows:

- Chapter two presents a review of literature and previous work related to this research.
- Chapter three presents the qualitative developed model.
- Chapter four presents the quantitative developed model
- Chapter five shows the simulation experiments along with results and analysis, and the development of the empirical relationships.

- Chapter six include the conclusions drawn from this work and recommendations for future work.

Finally, the thesis includes four appendices; these are:

- Appendix A: Publication Arising from This Work
- Appendix B: Additive Manufacturing Processes Classification
- Appendix C: Analysis of SL Process Parameters Literature Review
- Appendix D: SLA 5000 System

Chapter Two

2 LITERATURE REVIEW

In this chapter, an overview and background of additive manufacturing with its advantages and applications are presented. After that, different additive manufacturing processes are clarified. Then, the stereolithography process is described with its different parameters. Finally, a review of previous work related to this research is discussed and analysed.

2.1 OVERVIEW AND BACKGROUND

Additive manufacturing (AM) is a process which transforms the engineering design files into physical parts by adding material layer by layer. The technology started to develop in the late 1980's with a process called Stereolitography process (SL) being the most popular technology by that time. After that many different AM technologies that use different materials were developed.

At the beginning AM was used to build prototypes only that's why it was referred to as "Rapid prototyping"; after that, the technology was developed to produce tools and dies and was called "Rapid tooling". Nowadays, AM technology is used to build up final products with different materials; hence, it is now called "Rapid manufacturing" [5].

There are different terms which also describe the AM process such as layer manufacturing, direct digital manufacturing, and solid freeform fabrication [5, 11].

- Layer manufacturing: it is related to the way the process fabricates the parts by adding material in layers.
- Direct digital manufacturing: since the technology produces an end user item directly from a CAD data.
- Solid free form fabrication: due to the process capability of building complex geometric shapes without specific tool.

2.1.1 Additive Manufacturing Steps

Additive manufacturing process steps are summarized below in Figure 2-1. The process starts with a preparation of a 3D CAD model of the part. Then, the 3D CAD file is converted to a language that can be understandable by the machine. A Standard Triangular/Tessellation Language (STL)[1] is used to break down the geometrical representation of the object into a group of triangular facets; thus, it is now a tessellated and approximated version of the CAD model [12].

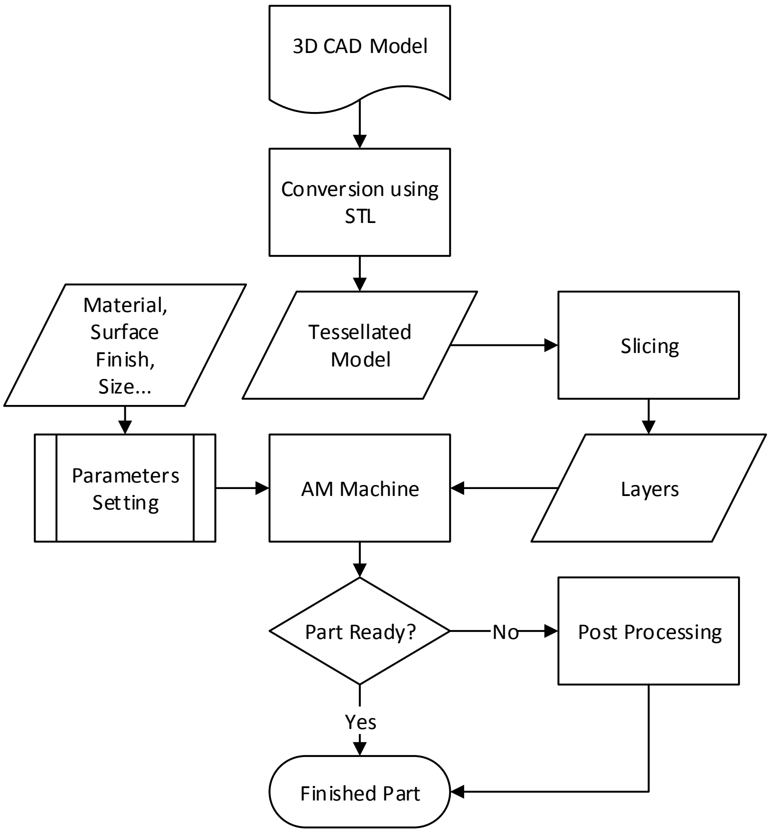


Figure 2-1: Additive manufacturing flow process diagram.

Then, a slicing technique is used to slice the model into very thin layers which are equal to the building layer thickness, then the file is transferred to the machine. At that stage, different process parameters are set for the machine depending on several factors such as the part material, product size required, surface finish … etc.

Subsequently, the part building process takes place, which differs from one technology to another. After removing the part from the machine, a post processing may be required

[1] STL is a standard file format for additive processes.

which differ from technology to another. This may include cleaning the part, removal of supports, depowder, post-curing, infiltration of resin/wax and drain excessive resin. Finally, the part is ready for usage [11].

2.1.2 Advantages and Applications

There are many advantages of using AM technology including [11, 13]:

1. Design freedom as it has the ability to change the design easily and quickly, thus eliminate penalty for redesign.
2. Shortening the new product development life cycle as it removes the lag time between design and production.
3. Reduce the product time to market as no special dies, tools or fixtures are needed.
4. Eliminate the production delays that occurs due to damaged or worn tools.
5. Economical for low volumes.
6. Builds very complex shape with good accuracy.
7. Inventory reduction as it is “just-in-time” operations.
8. Reduce the raw material usage and minimize the waste as leftover material can be reused (according to the technology).
9. Improve the facility layout, because a single machine is needed for building a part, thus reduces the conjunction between the flows.
10. Eliminate the need for assemblies, since the complex part (product) components are manufactured separately and then joined together due to geometric restrictions, complex parts (product) can now be made as a single piece.

Accordingly, AM has been used in many applications like aerospace, automotive, air craft, medical [14], biomedical [15, 16], dental restorations [17], electronics, jewellery, coin making, architecture and design, tooling and many other fields [2].

2.2 ADDITIVE MANUFACTURING PROCESSES CLASSIFICATION

AM has different technologies that are currently available or still under development. Each of these technologies may use different techniques in building the product or different materials. Consequently, there are several classifications to the AM which are classification according to the baseline technology, like whether the process uses lasers, printer technology, extrusion technology [18], specific details of the process embodiment (e.g., drop-on demand vs. continuous direct inkjet printing techniques) [19], the type of the input raw material (metal, polymer, ceramics , etc..) [5] , physical state of the starting raw material [18, 19] and the mechanism employed for transferring data from the sliced three-dimensional models into physical structures [20].

Since in AM process the primary function is to convert the raw material into series of connected layers, thus in this work, AM technology is classified according to the state of the processing material. It is a classification which collects different processes together according to material state. There are four states of materials that are widely used in AM; these are powder based, solid based, paste based and liquid based as shown in Figure 2-2. For each of these material states, there are different AM processes that are found in literature and that will be discussed briefly below and detailed in Appendix B. The technologies which are listed below are of the most commonly used processes in AM.

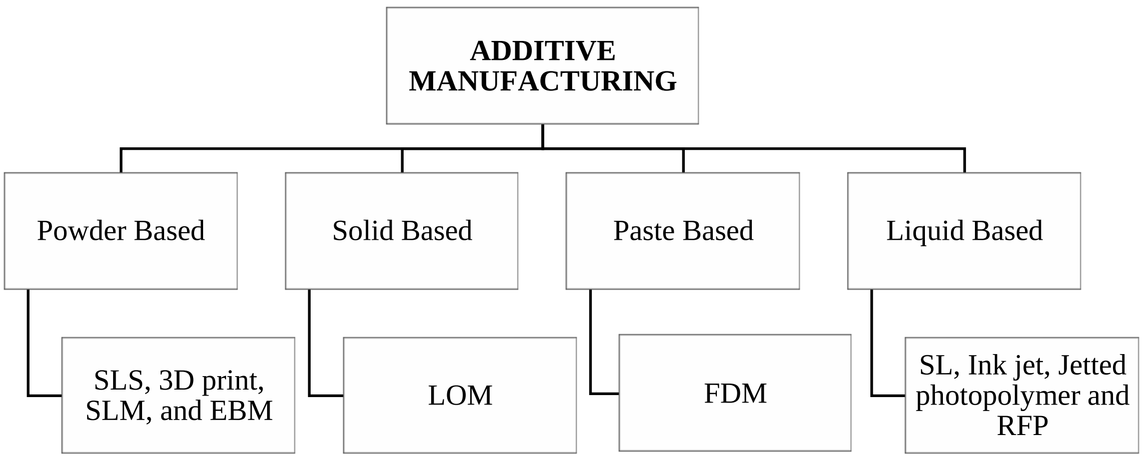


Figure 2-2 Additive manufacturing processes classification

2.2.1 Powder Based

Several processes use powder based material in the building process such as Selective Laser Sintering (SLS), 3D printing, Selective Laser Melting (SLM), and Electron Beam Melting (EBM). In general, using powder based material facilitates fabrication of parts with wider range of materials including polymers, wax, nylon/glass composite, powder metals, combination of metals and polymers, ceramics and combination of metals and ceramics [13].

SLS was the first developed powder based technology by Ross House-holder in 1979, but it was commercialized by Carl Deckard and Joe Beaman at the University of Texas, Austin, USA, in late-1980s [5, 6, 13, 21–23]. 3D Printing process was then developed by the Massachusetts Institute of Technology, USA, in the early 1990s [6, 14]. SLM was derived from SLS at the Fraunhofer Institute, Aachen, Germany, in 1995 [21, 24]. Finally, EBM was lately developed by the Arcam company of Sweden in 2005 [24–26].

2.2.2 Solid Based

In the solid based group the material is used in form of either very thin sheets of polymers and metal (less commonly), or layers of adhesive-coated paper [5]. The most popular machine in the solid based material is the Laminated Object Manufacturing (LOM). There are others solid based materials in AM but less commonly used as found in literature. LOM process was developed by the California-based Helisys Inc. (now Cubic Technologies) in 1991 [27, 28].

2.2.3 Paste Based

In the paste based group the material is available at low cost; the commonly used are ceramics, metals, and polymers such as acrylonitrile butadiene styrene, polyamide, polycarbonate , polyethylene, polypropylene, and wax [14]. One of the most used process in the paste based material is the Fused Deposition Modelling (FDM). FDM was developed by S. Scott Crump in the late 1980s and was commercialized by Stratasys in 1990 [6, 29].

2.2.4 Liquid Based

There are several processes which use the liquid based material in the building process such as Stereolithography (SL), Ink-jet, Multi-jet modelling and Rapid Freeze Prototyping (RFP). The most common used liquid material is photo-curable polymers but recently ceramics and metal parts are used by adding suspension of ceramic and metal particles in the photo-curable polymers vat [30].

SL was developed by Charles Hull in 1984, then in 1986 Hull patented his idea. It is the first AM process but still one of the most important process that uses liquid based material [6, 25]. SL is the focus of this work and will be discussed in details in section 2.3.

The ink-jet process was implemented by Solidscape in late 1980's [25, 31]. Jetted photopolymer was then developed by combining the techniques used in Inkjet Printing and SL [25]. Objet Geometries Ltd. and 3D Systems developed the jetted photopolymer machine. The machine was then commercialized in 2000 by Objet Company; while, 3D Systems commercialized it in 2003 [32].

RFP is the latest technology using liquid based material and is currently under development at Missouri University of Science and Technology and not yet commercially available [5, 33].

2.3 STEREOLITHOGRAPHY PROCESS

Based on the review presented in the previous section, it is clear that there is a wide range of liquid materials that can be used by AM technologies. SL process has a variety of liquid resin that are available; in addition, it has been one of the most significant AM technologies as it the best part accuracy compared to other AM processes [9]. It is one of the technologies that is considered to be suitable as a future manufacturing process. That's why it was selected in this work and this section provides further details about the technology. SL is a photo-polymerization process which changes the liquid photopolymer resin in to solid by using an ultra violet (UV) laser beam, thus it relies on laser power to converts a liquid resin into solid.

In 1987, 3D Systems introduced the first commercialized Rapid manufacturing technology system based on stereolithography (SL), and the system is called Stereolithography Apparatus (SLA)[2] [34]. Although many other techniques have been developed, SL remains one of the most powerful and versatile of all AM processes. It has the highest fabrication accuracy and an increasing number of materials that can be processed is becoming available [15, 30]. However; the parts produced by SL are still prone to unsatisfactory levels of quality due some reasons that will be discussed in 2.4.

2.3.1 Three Stages in Stereolithography Process

SL follows the same procedure explained in 2.1.1 above for building parts; however, the difference is in the building process and the post-curing. The three stages in the SL process are:

1. Pre-build stage: in which several preparation tasks before fabrication are performed like STL conversion, slicing and support generation (if needed).

2. Build stage: in which the building process of the part is carried out.

3. Post processing stage: in which cleaning, drain excessive resin and post-curing process (if needed) takes place.

In the second stage, the part building process in SL takes place on a movable platform which is positioned below the liquid resin surface as shown in Figure 2-3 . 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 keeps 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 (sweeper) slides over the vat for smoothing the surface before building the next layer. The platform is then lowered by a distance which is equal to the layer thickness and 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 [6].

SLA[2] Will be referred as stereolithography (SL) in the remaining text.

In the third stage, the part is then removed from the platform, if there are supports broke them, and the final part is cleaned from any excess liquid by using chemicals. 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 resin does not reach full solidification; therefore, after building in SL, the part is put into an oven to be cured up to 100% and to complete the polymerization (post- curing process) [10, 35]. (about 97% solidification is obtained during the building process) [36].

To sum up, among the discussed three stages, the building stage takes most of time. Accurate prediction of the time required for this phase is critical for various activities and depends on selection of build parameters.

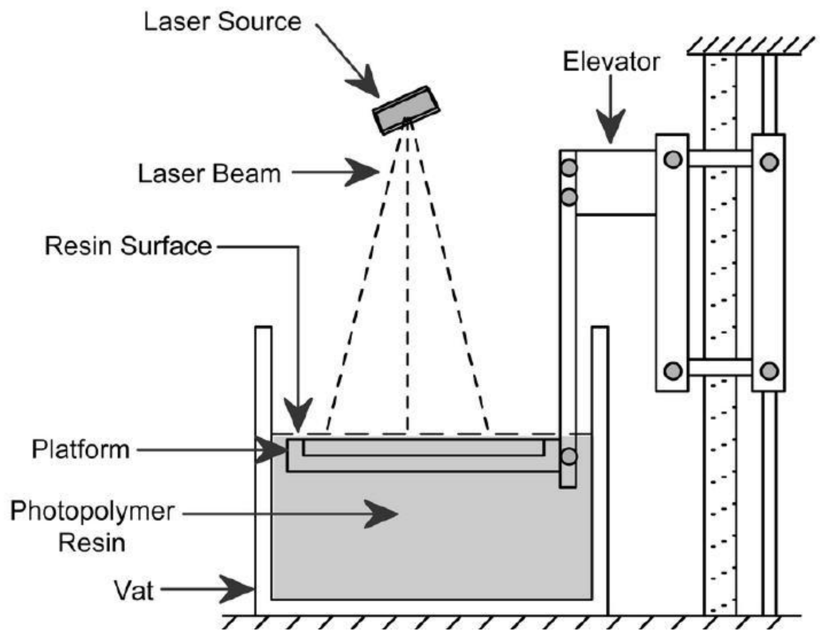


Figure 2-3: Stereolithography machine setup.

The Part quality in the SL process is a function of the many parameters. As mentioned by D. a. Schaub *et. al.* [37] "*the SL technology is very complex that has more than 50 process parameters variables"*. Furthermore, A. P. West *et. al.* [38] stated *"SL process is very complex even experienced operators may not be able to select appropriate variable values to achieve desired build objectives*". To complicate matters further, process parameters is one of five main sources that affect the quality of parts built using SL. These are discussed in more details in the next section.

2.4 RESEARCH INTO STEREOLITHOGRAPHY PROCESS

There are five main research areas which have greatly attracted researchers because of the huge effect these areas has on the SL part quality. These areas are converting the CAD to STL, material shrinkage, laser beam, post-curing process and process parameters setting. An accumulation of the above five errors usually causes 250–500 μm dimensional error and very unpleasant surface roughness, which make AM products unacceptable in some applications [34]. Thus, this has led to significant advances in developing new software, materials and composites, new build styles (laser scanning patterns), machine hardware and process parameters settings. Different advances in each of the five different areas are presented next.

2.4.1 Converting the CAD to STL

Most AM processes uses the STL file format to define the part before the building process as mentioned in 2.1.1. STL cause some problems like gaps, flip triangles, missing facets, overlapping facets, etc …[39]. Due to approximation of the 3D surface by triangular facets, some researchers focused on developing STL viewers and repair software such as Magic RP, Mini magic [18, 40, 41] and netfabb [42] as to view, analyze and correct the errors. Figure 2-4 shows how Mini Magic viewer found a problem and corrected it (a bad STL file by fixing the hole).

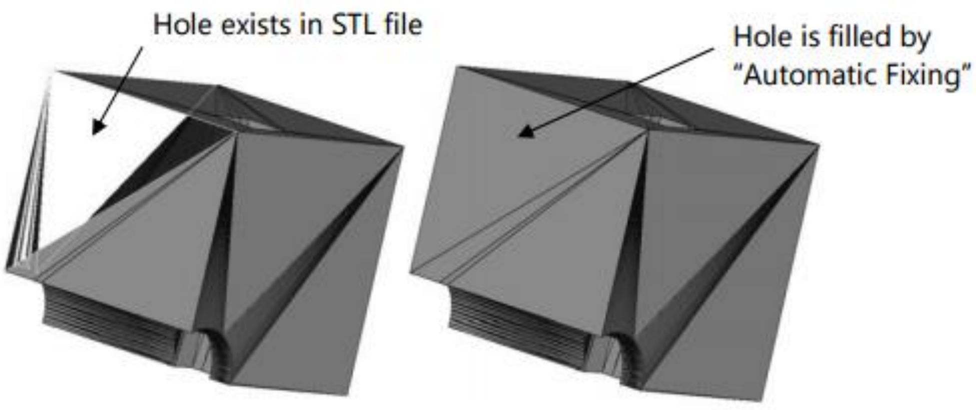


Figure 2-4: Bad STL file is fixed [40]**.**

2.4.2 Material Shrinkage

Some researchers focused on the material properties, as the first used material was acrylic resin, it was found that parts build with it have low part strength and high shrinkage [35]. Due to the bad results (low quality level) and unsatisfactory resin properties, different works were made in order to develop various types of composites with good properties investigating their effects on the part quality in order to improve it [15, 43–46].

2.4.3 Laser Beam

As the beam laser width is not constant during a single built some researchers focused in developing controllable software in order to control this problem. Then, they found that a finite beam width in some regions during building the part may results in dimensional inaccuracy, so they focused on developing software which varies the beam width and controls it during a single built (beam compensation). They found that changing the beam width during these two regions which are the boundary contour and inside of the part would minimize the dimension errors [47–50].

Other researchers modified the SL machine by replacing the laser beam with digital micro mirror device this act results in a faster building process with it a smooth curved surface without changing any value of parameters [51]. Moreover, replacing the UV laser in the conventional SL process with a carbon dioxide laser (CO_2) beam has resulted in very desirable physical properties [52]. Finally, adding another laser beam to the traditional machine in order to have two laser beams, this modifications has improved the part curing [53]. It should be known that SL commercial machines by 3D systems do not accept any modification has been in the research field.

2.4.4 Post-Curing Process

The post-curing process is a critical stage in the SL process. It is a process which is needed to cure any uncured liquid trapped in the part after finishing the building stage as stated before in 2.3.1. During post-curing stage internal stresses occurs from the thermal and ultraviolet exposure which results in part shrinkage [54]. Shrinkage occurrence in this stage plus what occurs during the photopolymerization process affects both the physical and mechanical properties of the part and therefore reduce the part quality.

It was found by researchers that the laser scanning pattern has a significant influence on the part quality such as dimensional accuracy, surface profile, process capability and building time, and is important for the stress distribution in building parts. So they investigated the effects of various existing building patterns (building styles[3]) on the part quality [55, 56]. They found that when the layers are scanned in only one direction, shrinkage forces occur mostly in this scanned direction. As a result, residual stresses occurs which is the main factor for part distortion, part delamination or cracks. Hence, many researchers focus on choosing the proper laser scanning patterns and developing new hatch styles [57–60] in order to improve the part quality. An appropriate scanning method can reduce shrinkage and avoid distortion.

2.4.5 Process Parameters Setting

Many researchers studied the parameters settings in order to improve the part quality. Studies by researchers reveal that the quality characteristics are related to the process parameters and can be improved with proper adjustment without incurring additional expenses for changing hardware and software [61].

Currently, there is a great amount of literature available for AM process parameters because it is one of the crucial problems that affect the part quality characteristics. There are different types of process parameters, which are categorized in to five classifications which are part parameters, machine parameters, resin parameters, platform parameters and recoat parameters as seen in Figure 2-5.

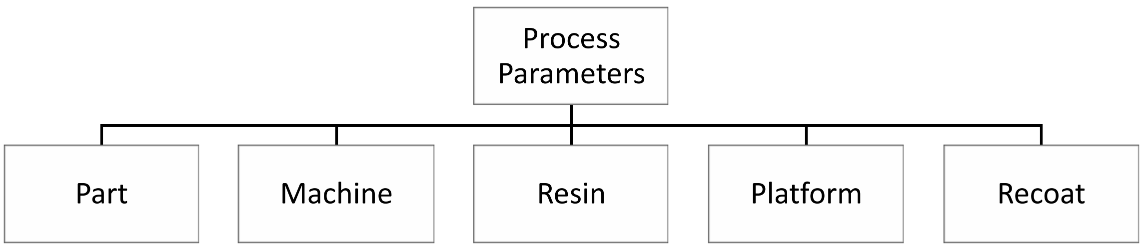


Figure 2-5: Classification of process parameters.

Building styles[3] is the hatch draw order sequencing

Part Parameters

E. R. Khorasani and H. Baseri [62] presented the following definitions for some of part process parameters which are shown in Figure 2-6:

- Layer Thickness (l_{th}): is the depth of a layer, the region that solidifies at the same elevation (mm).
- Over-cure (O_c): is the depth of a strand pierces in to the lower adjacent layer. This is what keeps the individual layers connected together to form a complete part. The presence of the over-cured is caused by over penetration of the laser beam in SL process (mm).
- Cure Depth (C_d): is the depth of strands (mm).
- 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 (mm).

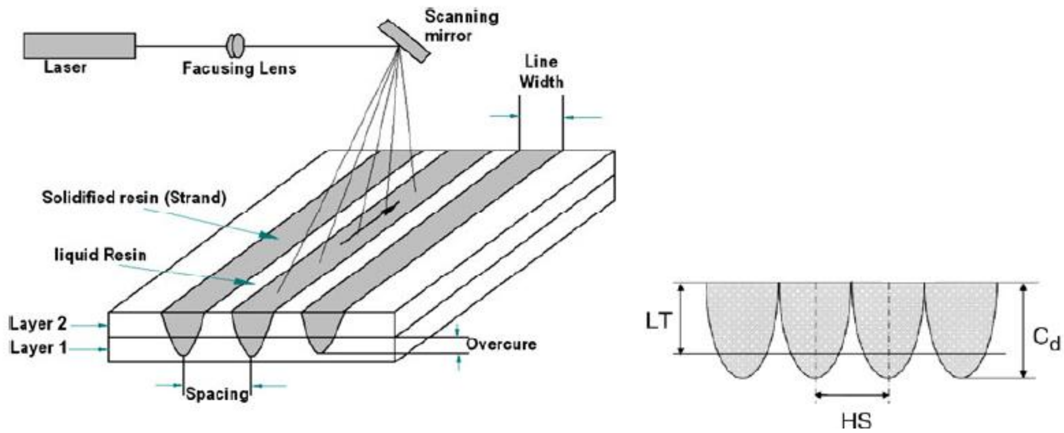


Figure 2-6: Process parameters in stereolithography [63].

Machine Parameters

Machine parameters differ from one SL machine to another depending on the specification of the machine. Generally, the machine parameters that can be adjusted when building a part are [18, 64]:

- Beam Radius (w_o): is the radius of laser beam focused on the resin (mm).
- Laser Power (L_p): the power of the laser beam (mW).
- Maximum exposure (E_{max}): is the Peak exposure of laser shining on the resin surface (centre of laser spot) or the exposure at the resin surface (mJ/mm^2).

- Scan Speed(S_v): Scanning speed of the laser that polymerizes the photopolymer resin (mm/seconds).

Material Parameters

The material parameters varies from one material to another; some of the material parameters are listed in [10, 18, 48]and are shown in Figure 2-7.

- Critical Exposure (E_c): is the exposure in which resin solidification starts to occur or it is the energy required for the photopolymer changes from liquid to gel phase (mJ/mm^2) or is the value characteristic of each polymer, under which the resin remains in the liquid state during the laser interaction.
- Depth Penetration (D_p): Measures of how deep light or any electromagnetic radiation can penetrate into a material. It is a point in which the power of laser decay to approximately $E_{max}/_3$ (mm).

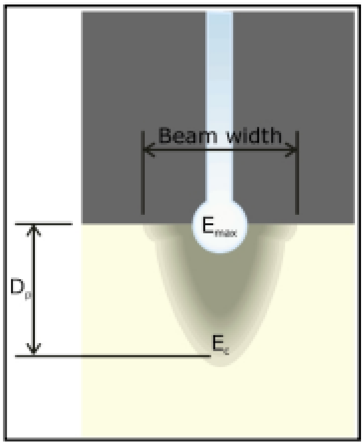


Figure 2-7: Resin parameters [23]**.**

Platform Parameters

The position of building the part and the angle of placing the part on the machine platform are important parameters. Figure 2-9 and Figure 2-8 show each of them [36, 50, 63, 65].

- Position of building: The various position in which the part is build (Horizontal/Vertical/Inclined).

- Angle of build (θ): is the building angle of the part according to the building platform.
- Angle of surface (θ_N): the angle between the vertical axis and normal to the surface axis.

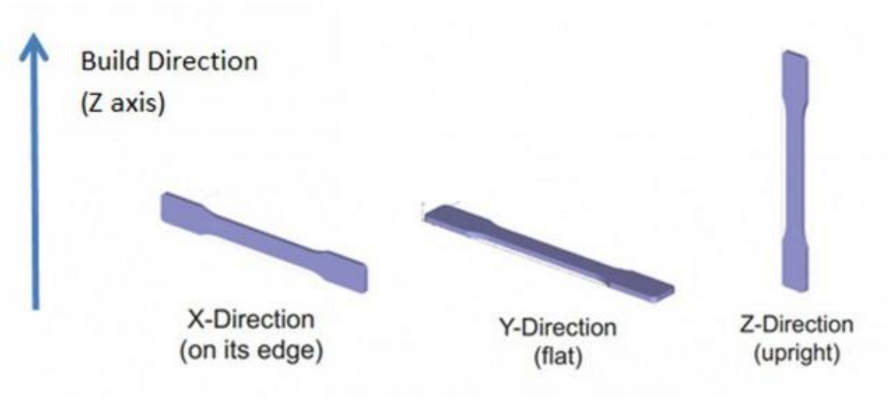


Figure 2-8: Building direction with respect to Z axis [66]**.**

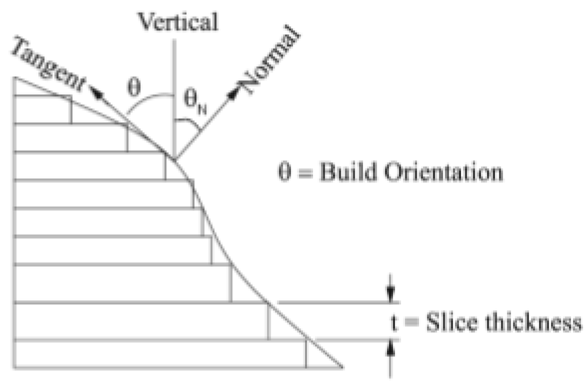


Figure 2-9: The build orientation angle and normal angle [67]**.**

Recoat parameters

A recoater mechanism is used to cover the previous layer with the material enabling the next layer to be scanned. Some of the recoat parameters are illustrated in [68] as seen in Figure 2-10.

- Blade gap: allows the vertical separation between the bottom of the recoated blade and the top of the previous (cured) layer to be increased per sweep (mm).
- Blade Velocity: the velocity of the blade (mm/seconds).
- Blade Width: is the width of the sweeper (mm).

- Recoater time/ sweep time: the time taken by the recoater to sweep over the part (seconds).

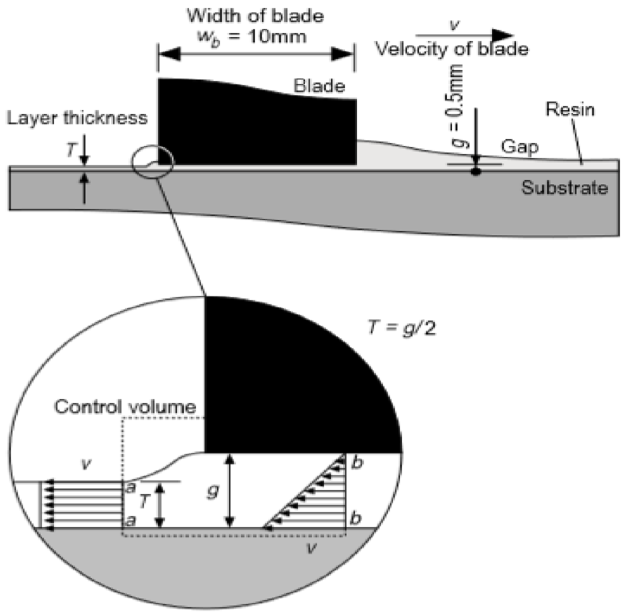


Figure 2-10: Recoat parameter [68] **.**

2.5 PREVIOUS STUDIES OF PROCESS PARAMETERS EFFECTS ON QUALITY CHARACTERISITCS

The process parameters affect the part quality characteristics* that are divided into physical characteristics and mechanical characteristics [30].

- The part physical characteristics are: dimensional accuracy, surface finish and distortion.
- The mechanical characteristics are: ultimate tensile strength, impact strength, flexural strength, yield, ductility, toughness, fatigue limit, compressive strength, hardness and density.

In addition, the process parameters affects the time of building a part, which, obviously, affects the cost of building that part. It will be illustrated below how the process parameters affects the part quality based on review of literature.

*Quality characteristics and part building time are collectively referred to as ***responses*** in this work.

2.5.1 Previous Research Approaches

Based on review of literature, it is evident that research into process parameters' setting generally follows either a descriptive or prescriptive approach:

1. Descriptive by studying the effect of the process parameters on the part quality and/or time. Also, to find the most significant parameter(s) that affect the different responses. This is done by conducting several experiments building actual parts or models of these parts.

2. Prescriptive by optimising the process parameters to obtain best achievable part quality characteristics.

Descriptive Approach

Some researchers conducted several experiments of building different parts to study the effect of process parameters on the part physical characteristics such as experiments to see the effect of the part orientation [50, 69–71], and laser exposure and laser scan speed [50, 72] on surface roughness. Other experiments were conducted to show the influence of the over-cure depth and layer thickness [73] , beam radius, laser power, and scan speed [47] on part building accuracy. In addition, investigating the effect of different parameters such as laser power, beam radius, resin critical exposure, resin depth penetration, scan speed, and hatch spacing on part building time and part accuracy [48]. Finally, studying the influence of both recoater sweep time and blade gap on the part height errors and build times [74].

Development of models such as simulation models using dynamic finite element (DFE) method rather than developing actual parts to test the effect of scan speed, and layer thickness lead to different shrinkage and curl distortion levels [75]. Also, a finite element method was used but with laser power, scan speed, and beam radius which simulated the curl distortion, shrinkage and building time [60].

Moreover, artificial neural network (ANN) models to predict the effect of layer thickness, hatch spacing, and over-cure on the part accuracy [76]. ANN was also used to predict the effect of layer thickness, over-cure, and hatch spacing parameters on the part accuracy[77]. In additional, ANN was used to predict the process building time based on layer thickness, part height and volume [78]. A mathematical solving software package was used to estimate the process building time based on some parameters as scan speed, cure depth, layer thickness, recoating time per layer; hatch spacing, part volume and laser power [79].

On the other hand, others conducted several experiments of building different parts to study the effect of process parameters on the mechanical characteristics such as experiments to see the effect of the layer thickness on flexural property, ultimate tensile strength, and impact strength (by conducting mechanical tests) [80] , the effect of part orientation on both part tensile strength and modulus of elasticity using design of experiments (DOE) [81, 82] and effect of hatch spacing on part hardness and part building time [35]. Finally, ANN and regression analysis where used to understand the effect of layer thickness and orientation on compressive strength [61].

Prescriptive Approach

Prescriptive approach is the other approach in the SL process parameters research; where, researchers focused on optimizing process parameters in order to improve the physical characteristics of built parts. Improvement of dimensional accuracy has been repeatedly addressed in literature either through optimisation of hatch spacing, coefficient of resin's shrinkage compensation (CRSC), the interaction between laser beam scanning speed and hatch spacing, and interaction between laser beam scanning speed and cured line width [83]; or optimising hatch spacing, laser scanning speed, layer thickness, and beam radius [30] by using Taguchi's method “Signal-to-Noise (S/N ratio)”. Genetic algorithm (GA) and simulated annealing (SA) were also used to find the optimum parameters values of layer thickness, over-cure, and hatch spacing to minimize the dimensional errors [62].

Moreover, layer thickness, hatch spacing, over-cure and cure depth were optimized by using Taguchi's method to improve the surface finish [59]. In addition, layer thickness, hatch spacing, over-cure, blade gap and position on the build plane were considered by using response surface methodology and analysis of variance (ANOVA) to obtain good dimensional accuracy and surface roughness [34]. Furthermore, by utilizing the Taguchi's method (S/N ratio) to layer thickness, hatch spacing, over-cure depth and post-curing time [84] , and developing an ANN to the hatch spacing, layer thickness and scan speed [85] the parameters were obtained to minimize the surface roughness and building time (multi objectives). Also, Taguchi's method was employed for optimizing both the over-cure and the hatch spacing in order to obtain a fully cured part without the need of the post curing process. This act results in minimizing both the shrinkage which occurs from the post curing process and the time of this process; and hence, improved the part accuracy and reduced the building time [10].

Further progress was made to improve the mechanical characteristics such as the part strength by optimizing different process parameters. For example, layer thickness, orientation, and post-curing time [36, 86] ; in addition, Layer thickness, degree of orientation, hatch spacing and post-curing time were optimized using DOE [63]. Furthermore, using Taguchi's method (S/N ratio), the layer thickness, degree of orientation and hatch spacing were optimized in order to enhance both the part strength and density analysis [87]. Finally, layer thickness, orientation, hatch spacing were optimized by ANOVA method to enhance the tensile, flexural and impact strength [88].

2.5.2 Summary and Analysis

According to the literature review conducted in this chapter, an analysis of literature is presented that focuses on the methodology used, parameters used, the different Quality characteristics (responses) and objectives. The analysis is based on 34 papers out of 110 papers in this work (refer to Appendix C for further analysis data).

Figure 2-11 shows that most of research were focused on improving the physical characteristics of the part with 62% followed by analysing the part completion time with 32% and finally improving the part mechanical properties with 29%.

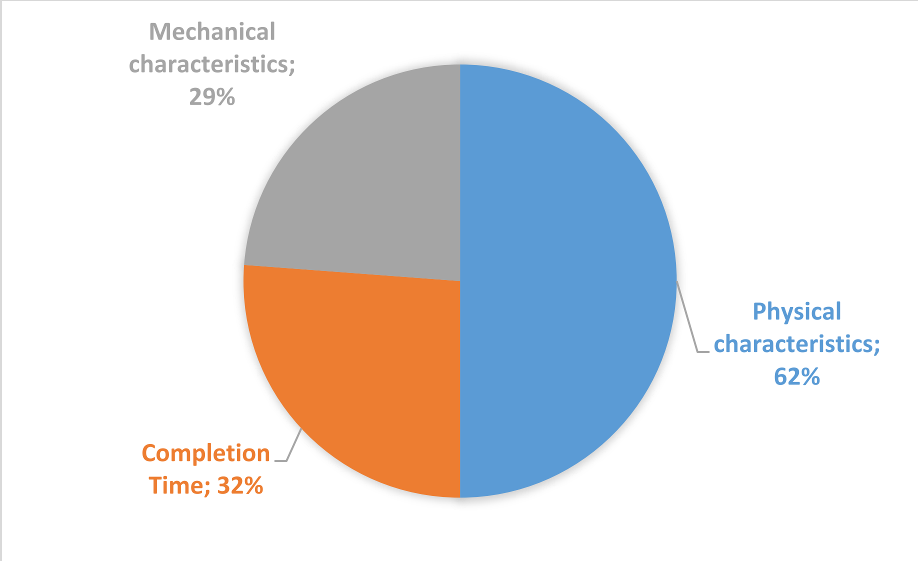


Figure 2-11: Analysis of responses.

Further breakdown of the responses that were used are shown in Figure 2-12. The bar chart shows that most researchers were focused on improving the part dimensional accuracy (35%). On the contrary, the compressive strength was the least addressed (3%).

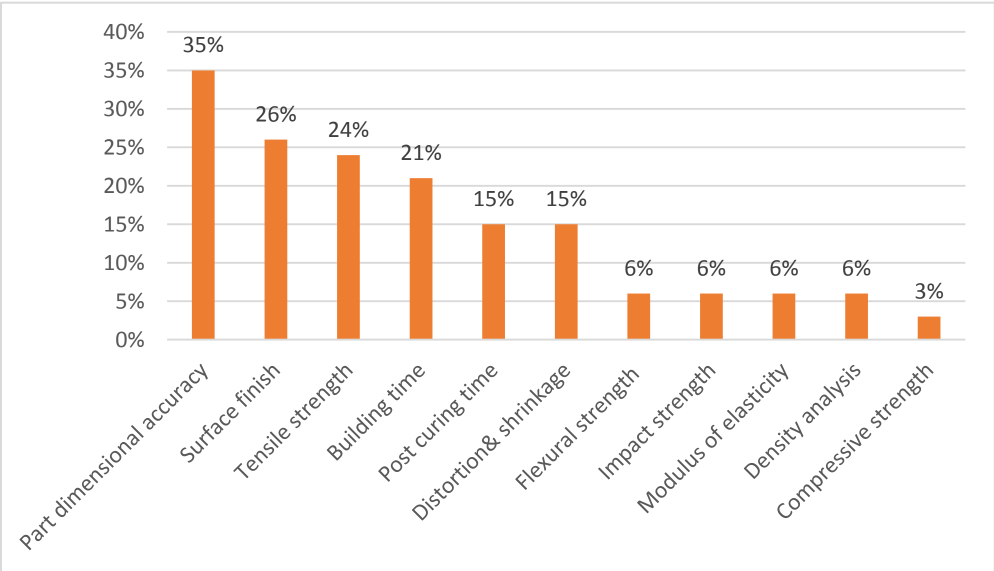


Figure 2-12: Different responses in literature.

A comparison of the different SL process parameters is shown in Figure 2-13. The SL process parameters were defined before in section 2.4.5. The bar chart illustrates that the interactions between the processes parameters were addressed only two times out of 34 papers.

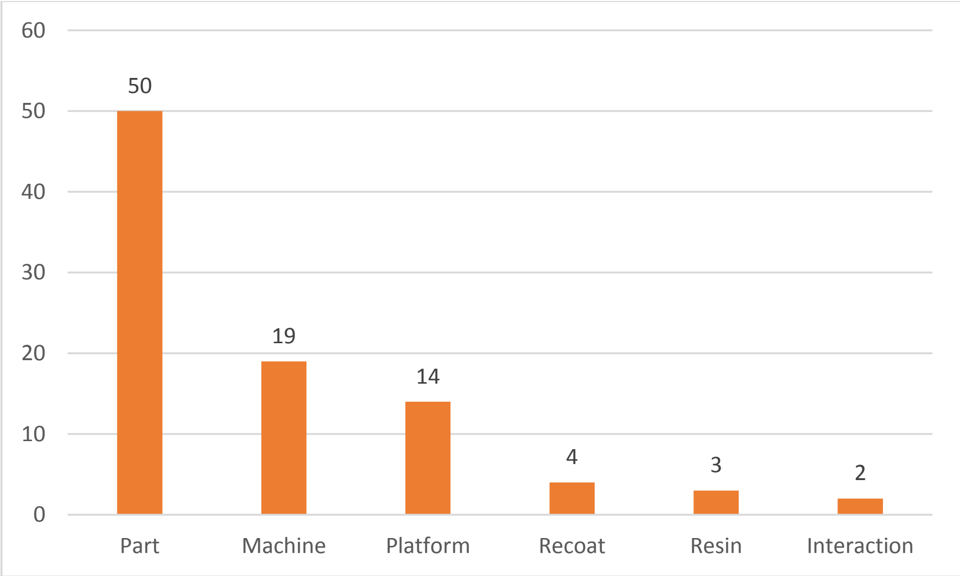


Figure 2-13: Process parameters bar chart.

The bar chart in Figure 2-14 shows different part, platform, recoat, resin, machine parameters percentage that were used in literature. It is shown that part height in the part parameter, CRSC in the resin parameters and the interactions between the parameters are the least used in literature with only 3%, on the other hand the layer thickness and hatch spacing in the part parameter, orientation angle in the platform parameter and the scan speed in the machine parameter are the most used parameters with 55%, 41%, 32% and 24% respectively.

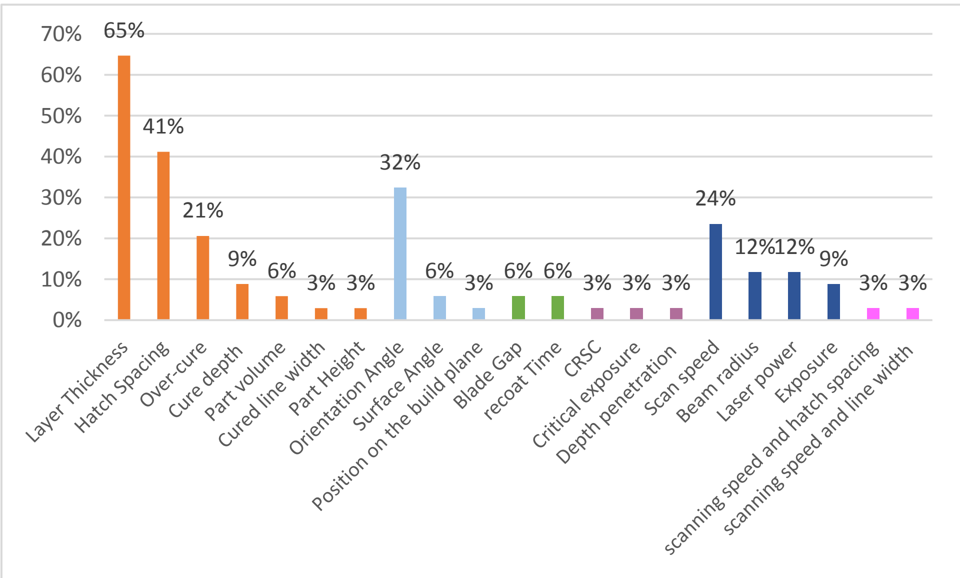


Figure 2-14: Different parameters.

The pie chart in Figure 2-15 shows the percentage of different methodologies that were used by researchers. It is clearly seen that DOE is the dominant method used in the case of the parameters setting with about 37%; while, the regression analysis, mechanical tests, GA and SA were the least used with only 3%.

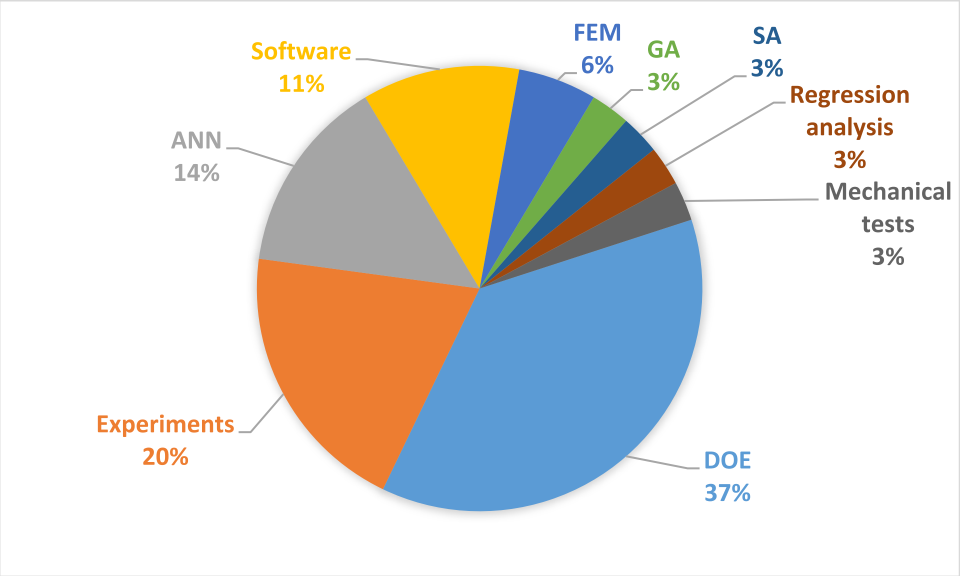


Figure 2-15: Different methodologies based on literature.

The pie chart in Figure 2-16 shows the main objectives of previous researchers in literature. Most of previous works were focused on optimizing the process parameters followed by finding the significant parameter to a specific performance measure (response) and how they affect them. These three objectives are the most used by researchers. On the other hand, modelling the SL process, finding empirical relationships and estimating the building time of the process were least addressed.

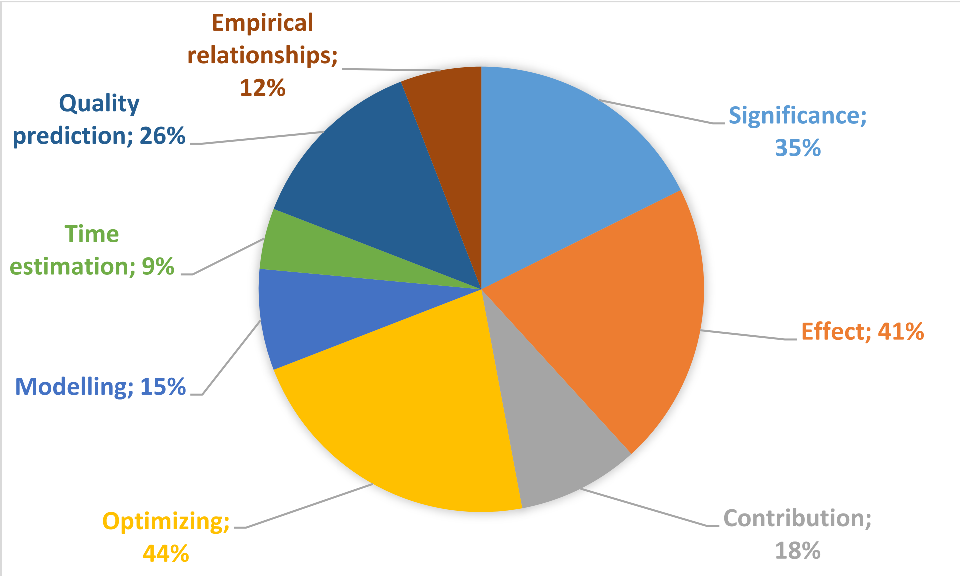


Figure 2-16: Different objectives by researchers.

Discussion

As illustrated above it can be concluded that the part completion time represent almost one third of the total literature focus becoming in the second position indicating the importance of this response.

The breakdown of responses showed that the top five responses that were studied by researchers were dimensional accuracy, surface roughness, tensile strength, building time and post curing time which are used in the development of the qualitative model that will be detailed in the next chapter.

Design of experiments was the most commonly used tool by researchers confirming the importance of finding the most significant process parameters and/or developing relationships between these parameters and responses. Moreover, optimizing different parameters, finding the significant parameter to a specific response and investigating the effect of the process parameters were the major focus of research while the time estimation, modeling the process and finding regression relationships between the parameters were minimally addressed.

Finally, the previous work studied many process parameters but the interactions between these parameters and how they may affect different responses and the whole system was rarely addressed. Accordingly, the interactions and interrelationships of the process parameters in the whole system is needed to be addressed. A system approach will be used in this work as it supports in understanding the behaviour of a system, helps in investigating the overall effect on changing any parameter on the system as a whole by modeling. Moreover, this approach will help in estimating the building time and finding new empirical relationships between process parameters and responses, which was not addressed before.

2.6 SYSTEM THINKING APPROACH

This section describes the main features of the system thinking approach, where these features are the main reason for selecting this approach. After that, some of the system thinking tools are clarified.

2.6.1 Overview

System thinking approach is a method which shift the traditional way of thinking in order to understand a complex systems in a different manner. Many people try to explain the system performance by showing how one set of event causes another. They seek to find a cause(s) that lead to an event, however, they ignore that this event may return to affect the same cause and leads to unanticipated results, ineffective policies and new future situations (problems). This act is called “feedback”, it should be considered in any system. As the interdependencies cause the behaviour of one element to affect other elements in the system a systematic thinking approach is needed to address all the above aspects.

One of the most common used system thinking approach techniques is System dynamics (SD). It was developed by Professor Jay W. Forrester of the Massachusetts Institute of Technology in 1961 [89]. SD is a powerful methodology which helps in visualizing the system structure, understanding, discussing, modelling and analysing a complex system. What makes this approach different from other available techniques is 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, it allows using feedback loops, time delays, and stock and flow which are essential for representing the dynamic nature of any system. In additional, SD can simulate the system behaviour in terms of graphs over time just by using mathematical equations.

2.6.2 Tools in System Dynamics

The system thinking method provides tools to better understand the overall behaviour of the system and helps in mapping the system structure these include: model boundary diagrams, subsystem diagrams, causal loop diagrams, stock and flow diagram and Policy structure diagrams.

Model Boundary Diagram

A model boundary diagram is a chart which shows the system boundary by listing the variables that are going to be inside the system (endogenous), outside the system boundary (exogenous) and the excluded ones in order to defines the scope of the model [90].

Subsystem Diagram

A subsystem diagram graphically shows the architecture of the system. It also shows the whole system as subsystems connecting each subsystem with other by an arrow representing the flows of material, money, goods, information, and so on [91].

Causal Loop Diagrams (CLD)

The causal loop diagram (CLD) one of the most used tools in SD [92]; it is different than the model boundary diagram and the subsystem diagram as they do not show the interrelationship between the variables they only show the boundary and the architecture of the model.

Stock and Flow

Stock and flow is a technique that shows the relationships among variables which have the potential to change over time. It illustrates the moving of materials, money and information through the system [93, 94].

Policy Structure Diagrams

These are causal diagrams showing the information inputs to a particular decision rule. Policy structure diagrams focus attention on the information cues the modeller assumes decision makers use to govern the rates of flow in the system. They show the causal structure and time delays involved in particular decisions rather than the feedback structure of the overall system [91].

2.6.3 Applications of System Dynamics

The system dynamics approach has been implemented in many areas such as supply chain management [95, 96], Healthcare [97, 98], Safety [93, 99, 100], financial [94, 101], capacity planning [102], water resources [103], and logistic outsourcing [104], but with few evidence of applications in the field of manufacturing processes [105] comparing to the other fields.

In the above fields, SD helped in understanding the system behaviour and making the right decision as it allows the user to see beyond the apparent behaviour, ability to predict the system behaviour in future, visualize any movement in the system/environment and finally system enhancement.

Chapter Three

3 QUALITATIVE MODEL DEVELOPMENT

As mentioned previously in section 2.6.2, causal loop diagrams (CLD) is one of the main tools used in system dynamics to develop qualitative models that shows the inter-relationships between different variables and that helps in identifying any feedback loops among variables. This chapter will show in details the steps in developing the CLD for the stereolithography process parameters and responses.

To the knowledge of this work, this is the first time the SL process parameters are modelled using system dynamics. The model is developed using Vensim PLE (Personal Learning Edition) simulation software, which is developed by Ventana Systems [106].

3.1 CAUSAL LOOP DIAGRAMS

3.1.1 Notations and Link Polarities

The CLD is a useful tool which graphically represents the system structure using simple notations; nodes and arrows. The nodes represent the variables while the arrows are the causal links that define the relationship between the variables; as seen in Figure 3-1.

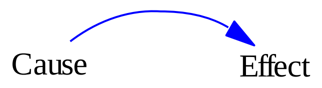


Figure 3-1: Causal relationship.

Causal link is assigned a polarity, either positive (+) or negative (-) to indicate how the independent variable (Cause) affects the dependent variable (Effect) as seen in Figure 3-2.

Figure 3-2: Positive and negative link polarities.

Positive links mean that if the cause increases, the effect increases above what it would otherwise have been, and if the cause decreases, the effect decreases below what it would otherwise have been. While, negative links mean that if the cause increases, the effect decreases below what it would otherwise have been, and if the cause decreases, the effect increases above what it would otherwise have been. Thus a positive (+) sign does not mean increasing but it means a direct relationship, while the negative (-) sign means an indirect relationship. Hence, link polarities describe the structure of the system; they do not describe the behaviour of the variables [91].

3.1.2 Feedback Loops

In many instances, the causal links form a "feedback loop" and; hence, a series of links causing output from one variable eventually influences input to that same variable. Thus, a feedback loop consists of two or more causal links between variables that are connected in such a way that if one follows the causality starting at any variable in the loop, one eventually returns to the first variable. The feedback loop also has polarity in order to trace the effect of change around the loop. It is either defined as a reinforcing or balancing loop as seen below in Figure 3-3.

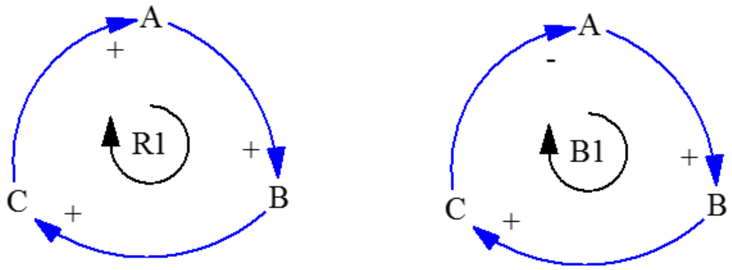


Figure 3-3: Feedback loop.

A **reinforcing loop** is a cycle in which the effect of a variation in any variable propagates through the loop and returns to the variable reinforcing the initial deviation i.e. if a variable increases in a reinforcing loop the effect through the cycle will return an increase to the same variable and vice versa.

Whereas, A **balancing loop** is the cycle in which the effect of a variation in any variable propagates through the loop and returns to the variable a deviation opposite to the initial one i.e. if a variable increases in a balancing loop the effect through the cycle will return a decrease to the same variable and vice versa.

3.2 DEVELOPMENT OF CAUSAL LOOPS DIAGRAM

Section 2.5 showed that the settings of different SL process parameters directly affect the quality and part completion time. For that, CLD is used to graphically represent the interactions between the SL process parameters to visualise the whole system and its process parameters in a structured manner and to show the cause and effect of each parameter on the other and on the system responses.

Four system responses are under study, which are the part dimensional accuracy, surface roughness, part completion time, and tensile strength. Different CLD models are firstly developed for each response, then all these models are combined in one single model to show the interactions between these four responses and different SL parameters setting.

3.2.1 Dimensional Accuracy

As indicated by literature, high degree of dimensional accuracy is required for SL applications and is one of the most addressed physical quality characteristic in research. Accuracy is influenced mainly by the curing (solidification) process; simply because if curing of layers and strands was not complete, deformation of built part will occur and; hence, the part's accuracy will be sacrificed. Curing is in turn affected by five different factors which are desired cure depth, laser power, resin characteristics, scan speed and laser spot radius, as seen in Figure 3-4. The effect of each of the five factors on curing is detailed next.

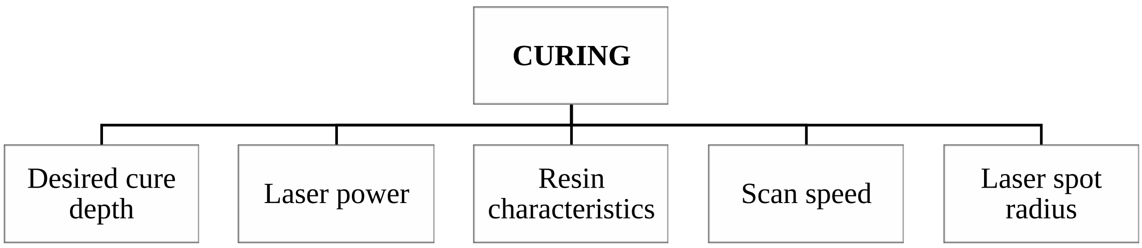


Figure 3-4: Different factors affecting the part curing

Desired Cure Depth

The Desired Cure Depth (C_d) directly affects Curing; the more the desired cure depth is, the less the curing is (and vice versa); hence, the negative relationship shown in Figure 3-5.

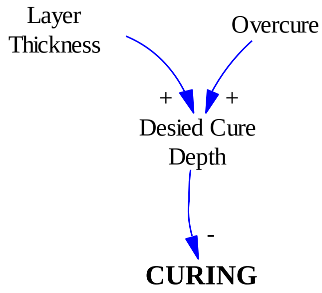


Figure 3-5: Effect of the desires cure depth on curing.

Desired cure depth, which is the depth of the strands formed by the laser beam. This is typically equal to the Layer Thickness (l_{th}) in addition to the depth penetrated by the laser beam into the lower adjacent layer, which is as mentioned before the Over-cure (O_c). This means that the greater the layer thickness and over-cure, the greater the desired cure depth is; and vice versa as indicated by the positive relationships in the CLD shown above.

Table 3-1 lists the statements that describe the relationships between the desired cure depth and the curing degree. These statements are extracted from previous work (source is shown in table as well).

Table 3-1: Relationships between the desired cure depth and curing degree.

Source	**Relationship(s)**
J. G. Zhou *et. al.* [34]	"Both over-cure and layer thickness will directly influence the cure depth. Over-cure affects the dimensional error so a low over-cure value is the best for small dimension errors"
G. V. Salmoria *et. al.* [35]	"To minimize the uncured resin regions, decrease layer thickness"
E. R. Khorasani and H. Baseri [62]	"As the layer thickness and over-cure increase, the dimensional error increases too"
G. Xu et. *al.* [73]	"Part over-cure depth has large influence on the part

	accuracy, as the over-cure depth increases the part accuracy decreases”

Laser Power

Figure 3-6 shows that when the Laser Power (L_p) increases (decreases) the energy per unit area, or simply Exposure Energy, increases (decreases) too. Increasing or decreasing the exposure energy in turn affects the solidification of the resin (Curing), which is a direct relationship in this case.

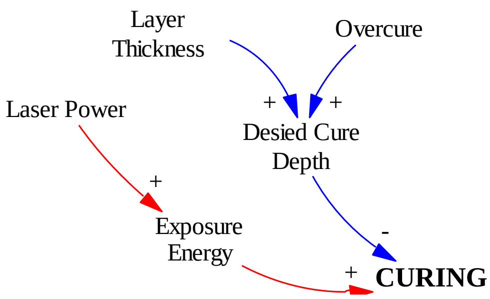


Figure 3-6: Effect of the laser power and exposure on curing.

Table 3-2 lists the different statements found in literature confirming the existence of a relationship between laser power, exposure energy, and curing.

Table 3-2: Relationships between laser power, exposure and curing degree.

Source	Relationship(s)
S. L. Campanelli *et. al.*.[10]	“The solidification of the liquid resin depends on the energy per unit area (exposure) left from the laser beam on the surface of the photopolymer”
G. V. Salmoria *et. al.* [35]	“Increasing laser power can affect energy density resulting in bullet-lines with a greater degree of cure”
C. Yi *et. al* [48]	“The power intensity of beam spot directly affects the curing characteristics”

Resin Characteristics

Curing also depends on the resin characteristics, as mentioned previously in section 2.4.5 the resin parameters are Critical Exposure (E_c) and the Depth penetration (D_p) which greatly influence the curing degree.

Since the part will not be fully cured unless the exposure value exceeds the resin critical exposure value; thus, lower E_c values means faster curing. Hence, the relationship between Critical Exposure and Curing is a negative one as shown in Figure 3-7.

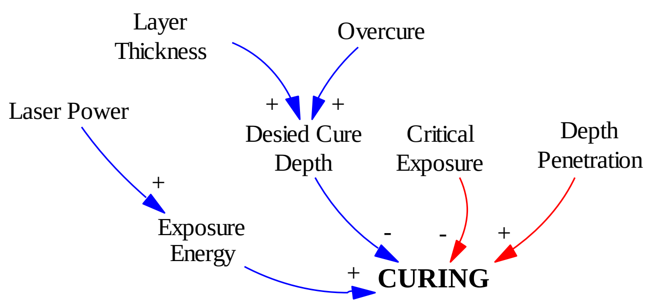


Figure 3-7: Effect of the resin on curing.

On the other hand, when the material Depth Penetration increases (decreases), the light or any electromagnetic radiation penetration into the material increases (decreases) too, which directly leads to increasing (decreasing) the Curing degree (note the positive relationship in Figure 3-7). Table 3-3 confirms these relationships by statements extracted from literature.

Table 3-3: Relationships between the resin parameters and curing degree.

Source	Relationship(s)
S. L. Campanelli *et. al.* [10]	"Polymerization is possible only when the exposure is greater than the critical value, otherwise the resin remains liquid"
B. Sager and D. W. Rosen [72]	"The curing process not only determined by process parameters such as laser beam power, irradiance profile, scan speed, laser beam angle with resin surface, but also the resin constants such as critical exposure and depth of penetration"

Scan Speed

Scanning speed (S_v) of the laser that polymerizes the photopolymer resin also affects curing. When the scans speed increases, the part is not fully cured. That's because the part should take the sufficient amount of energy per unit time to cure. On the other hand, slow scan speeds guarantees reaching the required curing degree. This inverse relationship is denoted by the negative link between Scan Speed and Curing in Figure

3-8; also, Table 3-4 lists the statements found in literature that confirms this relationship.

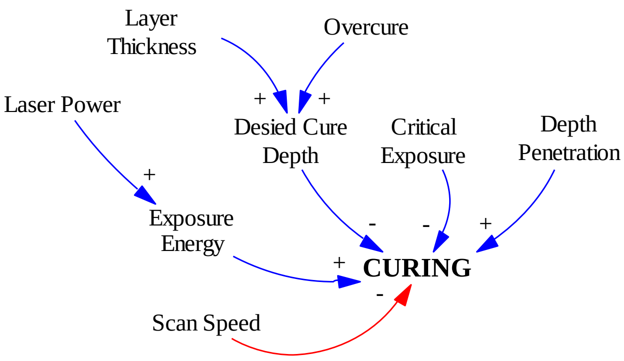


Figure 3-8: Effect on scan speed on curing.

Table 3-4: Relationships between the scan speed and curing degree.

Source	Relationship(s)
G. V. Salmoria *et. al.* [35]	"Slowing the scanning speed can affect energy density resulting in bullet-lines with a greater degree of cure"
C. Yi *et. al.* [48]	"We should decrease the scanning speed to guarantee the curing degree"

Laser Spot Radius

Beam radius or Spot Radius (w_o) is the radius of laser beam focused on the resin. Also, the Hatch Spacing (h_s) is the distance between two successful movement of laser with a specific Spot Radius. Thus, as shown in Figure 3-9, as the laser beam spot radius increases (decreases) the hatch spacing increases (decreases) too. Increasing the Hatch Spacing generates an overlapping area which is required to guarantee that continuous connection between the strands is provided; however, increasing the Overlapping Area excessively allows liquid resin to be trapped in the part, thus curing decreases. Hence, the negative relationship between the Overlapping Area and Curing shown in the figure below.

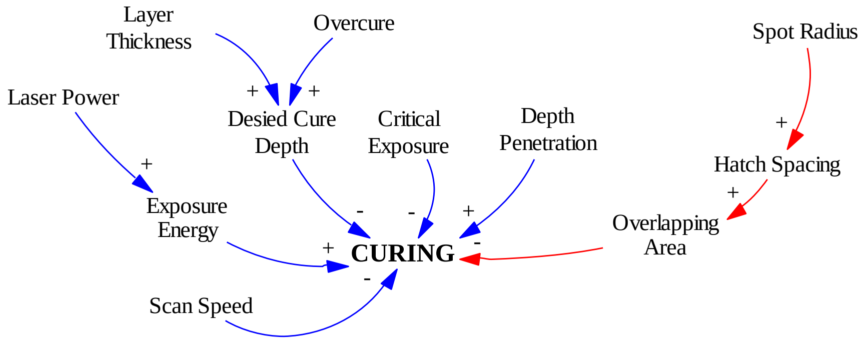


Figure 3-9: Effect on laser spot radius on curing.

Figure 3-10, shows how large hatch spacing distance makes large overlapping area, thus un-cured region between the two parallel hatch lines.

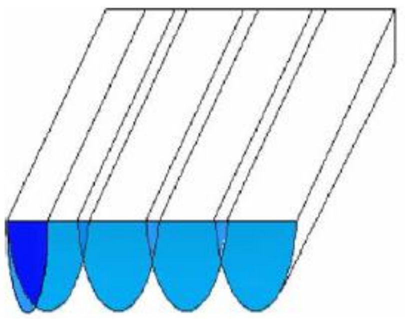


Figure 3-10: Results of a large hatch space [48].

Again, these relationships are confirmed by evidences from literature which are listed in Table 3-5.

Table 3-5 : Relationships between the laser spot radius and curing degree.

Source	**Relationship(s)**
S. L. Campanelli *et. al.* [10]	"An overlap between two adjacent scanning vectors is needed to provide a continuous connection"
G. V. Salmoria *et. al.* [35]	"The use of lower line hatch spacing will produce a more compactly cured structure, presenting smaller regions of uncured resin"
C. Yi *et. al.* [48]	"The more the overlapping area is, the more reduction in the part accuracy resulted from a very large hatch spacing"
E. R. Khorasani and H. Baseri [62]	"A medium hatch spacing is a positive factor to the part accuracy to bond the parts"

Curing Effect on Accuracy

After showing the interrelationships between the five factors that influence the curing process (as shown in the developed CLD; Figure 3-9), it is important to describe how the curing process affects the part accuracy. The CLD developed is further extended to include the effect of Curing on Accuracy as shown in Figure 3-11.

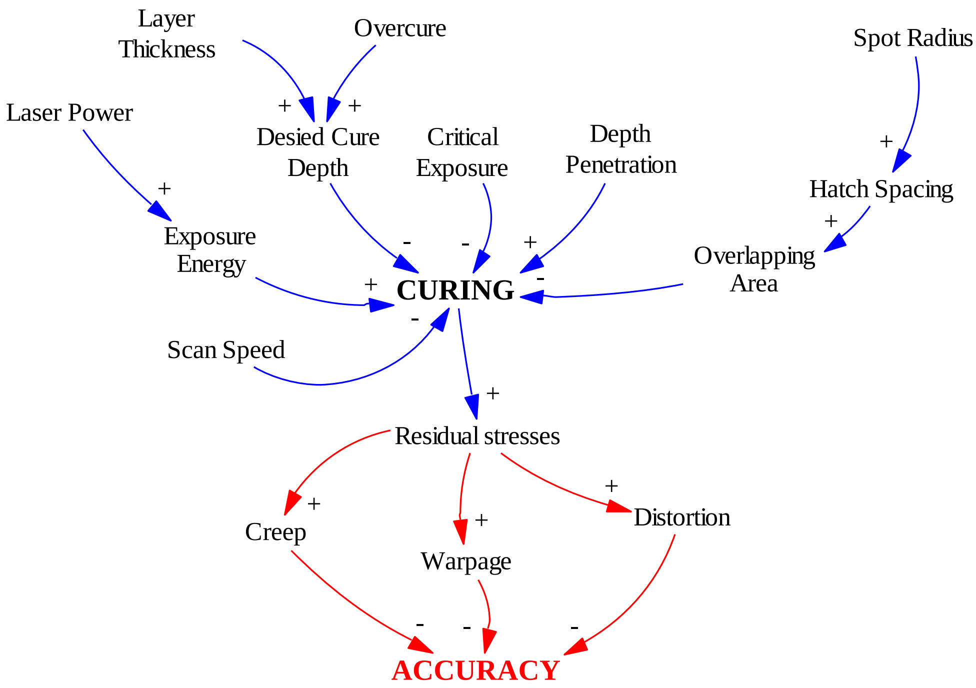


Figure 3-11: Effect of curing on the part accuracy.

The Curing process is a vital process in the SL process; however, excessive curing will result in residual stresses which cause part distortion, warpage or creep.

Hence, the overall effect of increasing curing excessively would be decreasing the part accuracy and vice versa; as indicated by the negative polarity of the links connecting to Accuracy in the CLD model shown above.

Secondly, the effects of hatch distance on the part accuracy is shown in Figure 3-12. As the hatch spacing decreases the overlaps area decreases (but it must be present). Then, the curing degree increases which increase the bonding between the two adjutant hatches lines thus accuracy increases (strands are bonded together strongly).

From the two CLD in Figure 3-11 and Figure 3-12, it is established that there is a conflict in setting the hatch spacing value. Too large hatch spacing makes a large overlapped area which contains liquid resin that is not fully cured; while, too small hatch spacing will not lead to bonding. To conclude, hatch spacing should be a medium value so the curing vectors will overlap causing a completely solid layer [62].

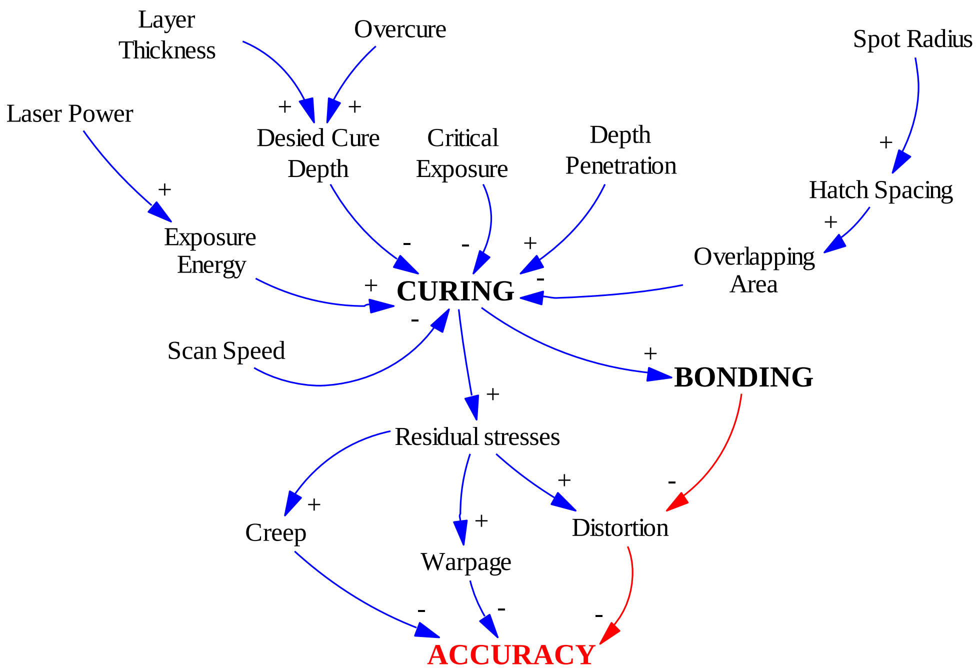


Figure 3-12: Hatch spacing distances effect on the part accuracy.

3.2.2 Roughness

The part surface finish is a vital characteristic in many applications; a poor surface finish limits the use of AM in some applications and; hence, it is important to be considered [51] . As stated in 2.5.1 the surface roughness is highly affected by different parameters, some of them will be explained below.

The AM technology due to its machining characteristics (building a layer upon layer) may results in phenomena, which is called the stair stepping effect. It is ridges which appear in the final component as a result of the layer building process as seen Figure 3-13. The stair stepping results in lowering the surface quality of the part [72], this phenomena "stair stepping effect" cannot be avoided but it can be minimized by selecting the proper parameters.

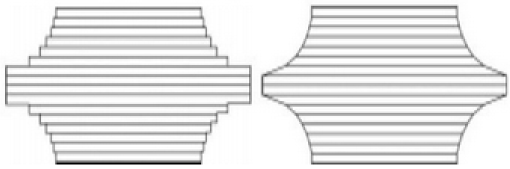


Figure 3-13: Stair stepping phenomena on contour shape

There are three parameters which mainly affects the surface roughness in SL process which are the layer thickness, the part deposition angle and the shape complexity. Development of CLD diagrams to show the effect of the three parameters on surface roughness is discussed next.

Layer Thickness

There is a direct relationship between Layer Thickness and Roughness, which was reported in literature (as listed in Table 3-6). The CLD for Roughness development starts by establishing this relationship as a positive one as seen in Figure 3-14. Meaning, when the layer thickness increases (decreases) the surface roughness increases (decreases) too.

Table 3-6: The effect of the Layer thickness on the surface roughness.

Source	Relationship(s)
N. Raghunath *et. al.* [13]	"The decrease in layer thickness affects the stair stepping significantly"
N. Raghunath *et. al.*[13], B. Sager and D. W. Rosen [72], E.-D. Lee *et. al* [85], and I.. B. Park *et. al.* [107]	"The smaller the layer thickness is, the better the surface roughness"

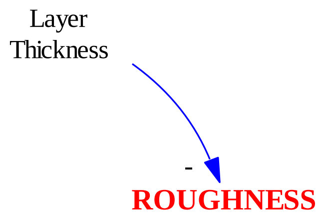


Figure 3-14: Effect of layer thickness on surface roughness.

Part Deposition Angle

There are various positions in which the part can be built; such as, horizontal, vertical, and inclined. These positions are set in the SL machine by two parameters; Orientation Angle (θ) and Surface Angle (θ_N).

As mentioned in [65], the summation of orientation angle and the angle of the surface is equal to 90 degree. Both angles affect part roughness and proper selection of the part orientation can reduce its roughness and improve its surface finish as mentioned in literature.

Table 3-7: The effect of the orientation on the surface roughness.

Source	**Relationship(s)**
Benay Sager and David W. Rosen [50]	"When θ is small , the angle between the laser beam and vertical is large but attainable surface roughness is very small, which results in better surface finish"
Y. Chen and J. Lu [69]	"The larger the angle between the scanning direction *r* and the surface normal *n* is, the rougher the surface will be"
I. H. Mulyadi [70]	"The stair stepping effects is creating by the orientation angle"
B. Sager and D. W. Rosen [72]	"Better up facing surface finish is possible by changing the angle of the build surface"
H. Kim and S. Lee [108]	"The optimization is performed to minimize the area of faces with rough surface angles and to maximize the area of faces with smooth surface angles"

Extending the CLD developed in the previous section by including the orientation effect on Roughness is illustrated in Figure 3-15. The CLD now shows that as the orientation angle increases (decreases), the surface angle decreases (increases); hence, the negative link between the Orientation Angle and the Angle of the Surface. The Angle of the Surface in turn affect the Roughness directly (positive relationship in the figure).

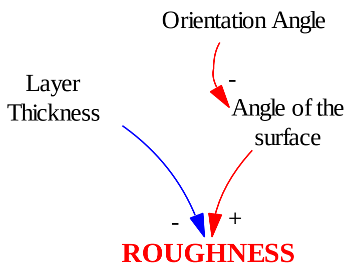


Figure 3-15: Effect of orientation on surface roughness.

Shape Complexity

Shape complexity, in terms of the curves and inclinations required to be built, affects the surface roughness due to the stair stepping phenomena mentioned earlier, as confirmed from literature in Table 3-8. Figure 3-16, shows that the more curves and inclinations of the part, the more complex the part is (and vice versa) and; consequently, the more the roughness is (as denoted by the positive relationships between all variables).

Table 3-8 : The effect of the curved shape on the surface roughness.

Source	Relationship(s)
Y. Chen and J. Lu [69]	"Inclined planes or curved surfaces along the build orientation have large staircase effect, thus have higher surface roughness compared to parts built with only vertical surfaces"

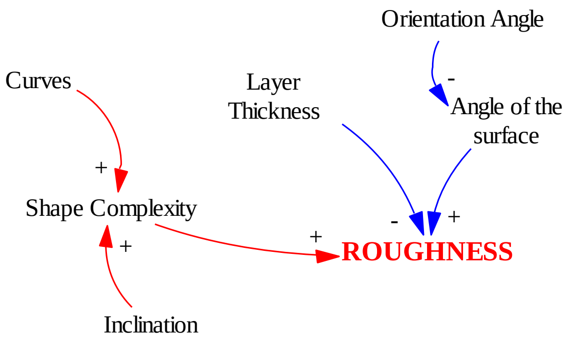


Figure 3-16: Effect of shape on surface roughness.

3.2.3 Part Completion Time

The total time needed to complete a part using the SL process is comprised of part preparation time, building time, removal from platform, cleaning, and post-curing time.

However, the building time, compared to the other time elements, takes most of the time.

Part Building Time

There are many parameters that affect the part building time; such as the layer thickness, part dimensions, over-cure, scan speed, laser power and laser spot radius.

<u>Layer Thickness and Part dimensions</u>

The effect of layer thickness and part dimensions on the part building time is modelled using the CLD diagram in Figure 3-17. The figure shows that when the Layer Thickness decreases (increases) the Number of Layers increases (decreases), thus the Building Time increases (decreases). Moreover, as the Part Height increases (decreases) the Number of Layers needed to produce the part increases (decreases) too, which in turn increases (decreases) the building time. Furthermore, as the part width increases (decreases) the Number of Stands needed to produce a layer increases (decreases) too. In additional, as the part length increases (decreases) the time needed to build a single Stands increases (decreases) too thus the overall building time will increase. Finally, when the layer thickness increases (decreases) the desired cure depth will increase (decrease) also resulting in increasing (reducing) the building time.

Table 3-9 shows how the layer thickness and part dimensions affects building time as stated in literature.

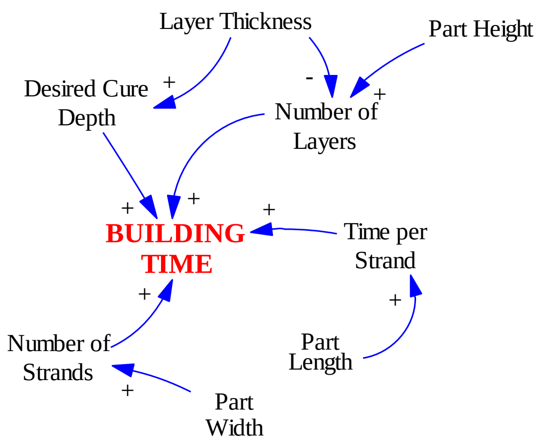


Figure 3-17: Effect of the layer thickness and part dimensions on the building time.

Table 3-9 : The effect of the layer thickness and part dimensions on the building time.

Source	**Relationship(s)**
H. Kim and S. Lee [108], E.-D. Lee *et. al.* [85] , and I. B. Park *et. al.* [107]	"Increasing the layer thickness will reduce the time"
Y. Li and J. Zhang [109]	"As the part height increase the number of slices increase thus time increase"

Over-Cure Effect

K. P. Roysarkar *et. al.* [84] addressed the effect of over-cure on part building time in their work as follows "the parameter, which largely influences the build time of the SLA part, is the cure depth".

As seen below in Figure 3-18, as the Over-Cure increases the Desired Cure Depth increases which also increases the part Building Time; and vice versa. This is indicated by the positive links shown in the CLD below between the different variables.

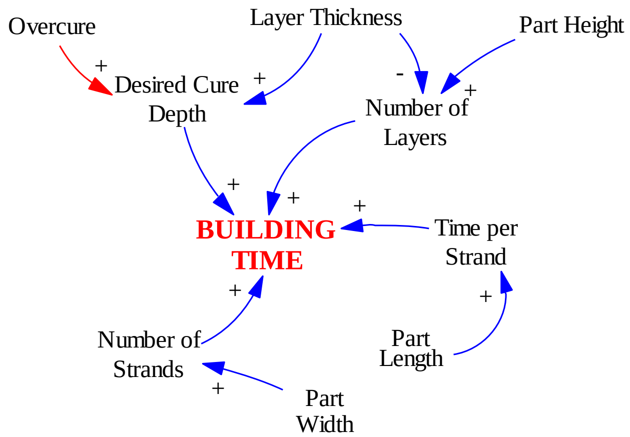


Figure 3-18: Effect of the over-cure on the building time.

Scan Speed

Z. Chen *et. al.* [30] stated that "that a lower scan speed resulted in time consuming fabrication process". The developed CLD is extended to include this relationship as shown in Figure 3-19; as the Scan Speed increases the Building Time decreases and vice versa. Hence, the negative relationship between these two variables.

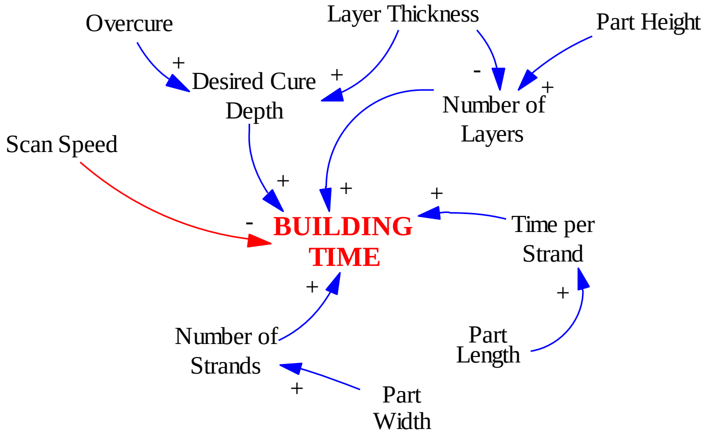


Figure 3-19: Effect of the scan speed on the building time.

Laser Power

J. G. Zhou *et. al.* [34] confirmed in their work that "Large laser power reduces the exposure time, thus reduces the building time". Exposure Time is affected by Exposure Energy that is needed to cure the part, which is directly affected by the Laser Power.

Thus, as the Laser Power increase (decrease), the Exposure Energy increases (decreases), Exposure Time decreases (increases), which leads to decreasing (increasing) the part Building Time. These relationships are illustrated by the further developed CLD diagram in Figure 3-20.

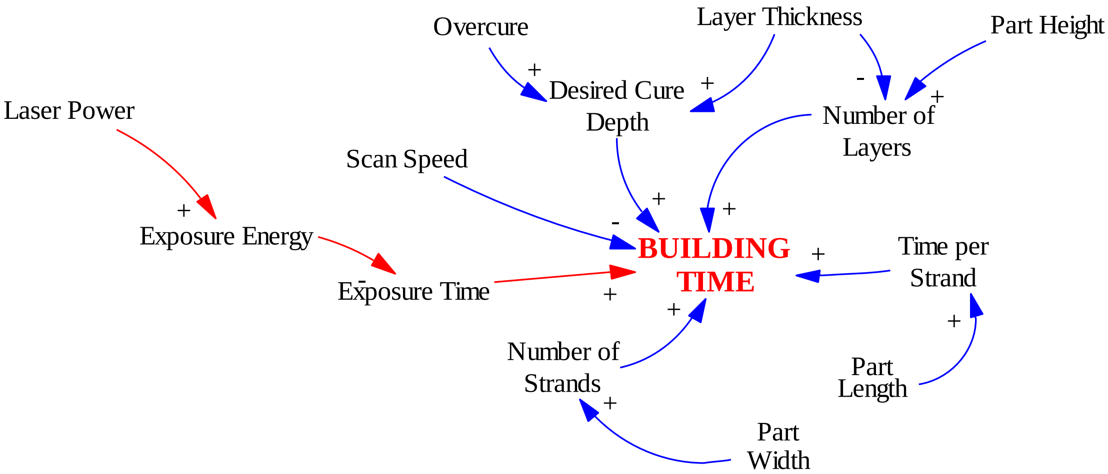


Figure 3-20: Effect of the laser power on the building time.

Laser Spot radius

As shown below in Figure 3-21, the laser Spot Radius affects building time, as the spot radius increases, the hatch spacing increases too, which decreases the number of scanned lines; thus, the building time decreases.

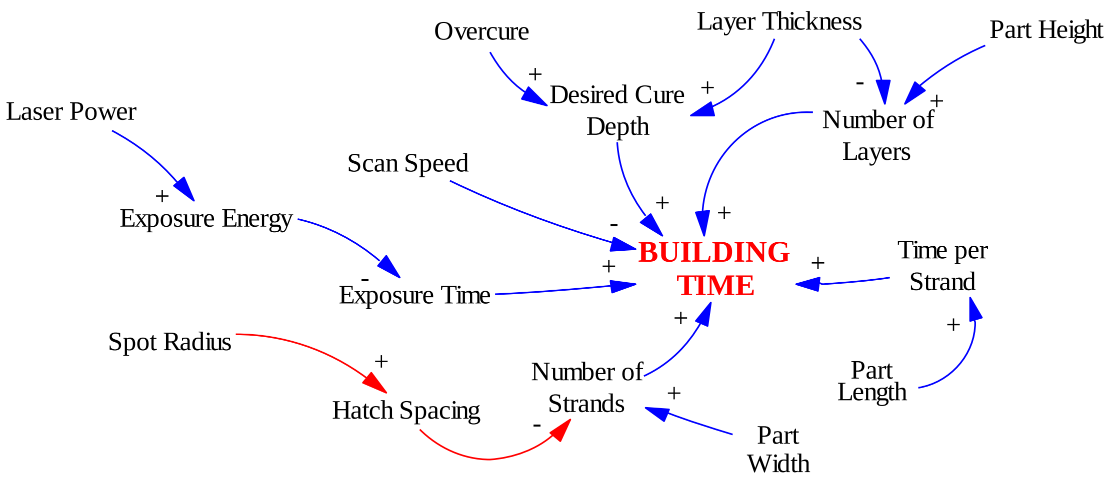


Figure 3-21: The effect of the laser spot radius on the building time.

Table 3-10, shows how the laser spot radius affects building time from previous work with references.

Table 3-10: The effect of the laser spot radius on the building time.

Source	**Relationship(s)**
G. V. Salmoria *et. al.* [35]	"The use of lower line hatch spacing will produce a more compactly cured structure, presenting smaller regions of uncured resin, but it requires more time"
C. Yi *et. al.* [48]	"The increase of Hatch spacing can decrease the number of scanning lines in each layer, and the internal scanning process takes most time of the building process"

Post-Curing Time

Post-curing time is the time spent by the completed part in the UV chamber to be cured after the SL building process [36]. The post-curing process affects both the physical and mechanical properties; in addition, it affects the overall time.

As seen before in Figure 3-10, a large hatch spacing generates a big overlapping area which allows liquid resin to be trapped in the part, thus curing decreases as shown in

Figure 3-22. Thus, in order to obtain a fully solidified part, the part will be placed in an oven/furnace [3]. The duration a part spends in an oven/furnace varies from part to part and that because of the resin type.

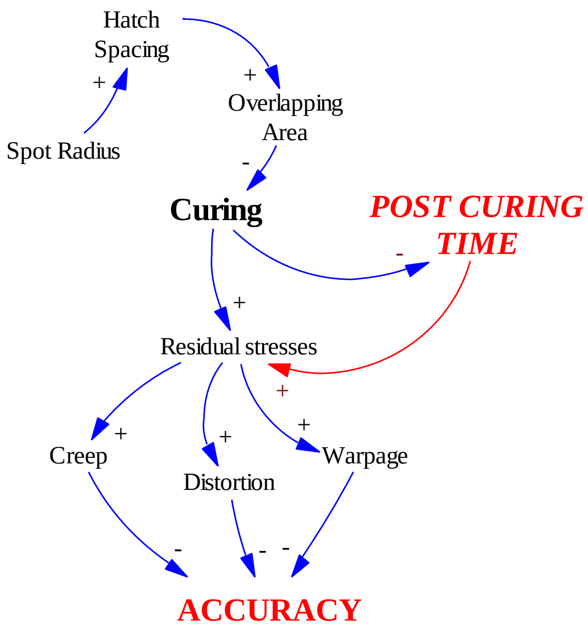


Figure 3-22: The effect of the hatch spacing on the post-curing time.

The CLD also shows that as the part curing degree decreases (increases) the part will take more (less) time in the post-curing process. However, as much as the post-curing process is important to the part curing and some mechanical characteristics, too much post-curing will lead to residual stresses that cause many problems as stated in 3.2.1. This was confirmed by several statements found literature and listed in Table 3-11.

Table 3-11: The effect of the hatch spacing on the post-curing time.

Source	**Relationship(s)**
R. Hague *et. al.* [3]	"During a thermal post cure cycle, part becomes more brittle; this consequently reduces the impact strength and the % elongation at break" "The mechanical properties can be adjusted according to the post-curing methodology used which may be desirable in the design of the end use part"
G.V. Salmoria *et. al.* [35]	"Green parts with different degrees of cure can present a disproportional shrinkage effect generating internal stress, which can lead to distortion and low strength"

G.V. Salmoria *et. al.* [46]	“Post-curing is essential after the SL process to increase the part strength and hardness because sometimes the part produces from SL seems to be sticky” “The shrinkage resulting from the cure process can reach values of up to 8% by volume ”

3.2.4 Tensile Strength

Tensile strength is the final response considered in this work, which is critical to several applications such as in mould dies [36, 80, 87].

B. S. Raju *et. al.* [80] stated that “the ultimate tensile strength decreases directly with increase in Layer thickness”; hence, Tensile Strength is directly affected by the Layer Thickness as shown in Figure 3-23. The negative link between the two variables means that to increase the part tensile strength the layer thickness should be decreased; and vice versa.

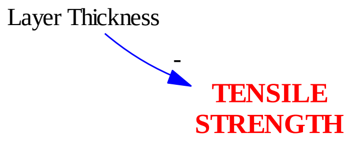


Figure 3-23: Layer thickness effect on tensile strength.

3.3 CONFLICTS IDENTIFIED

In this section, all the previously developed casual loop diagrams for establishing the relationships of the SL process parameters, their interactions, and their effect of the dimensional accuracy, roughness, building time, post curing time and tensile strength responses are integrated into one CLD model shown in Figure 3-24.

From the figure, Conflicts between the process parameters and the responses are evident. As seen below in the CLD diagram, there are four process parameters which affect the responses differently. These parameters are the layer thickness, over-cure, spot radius and scan speed.

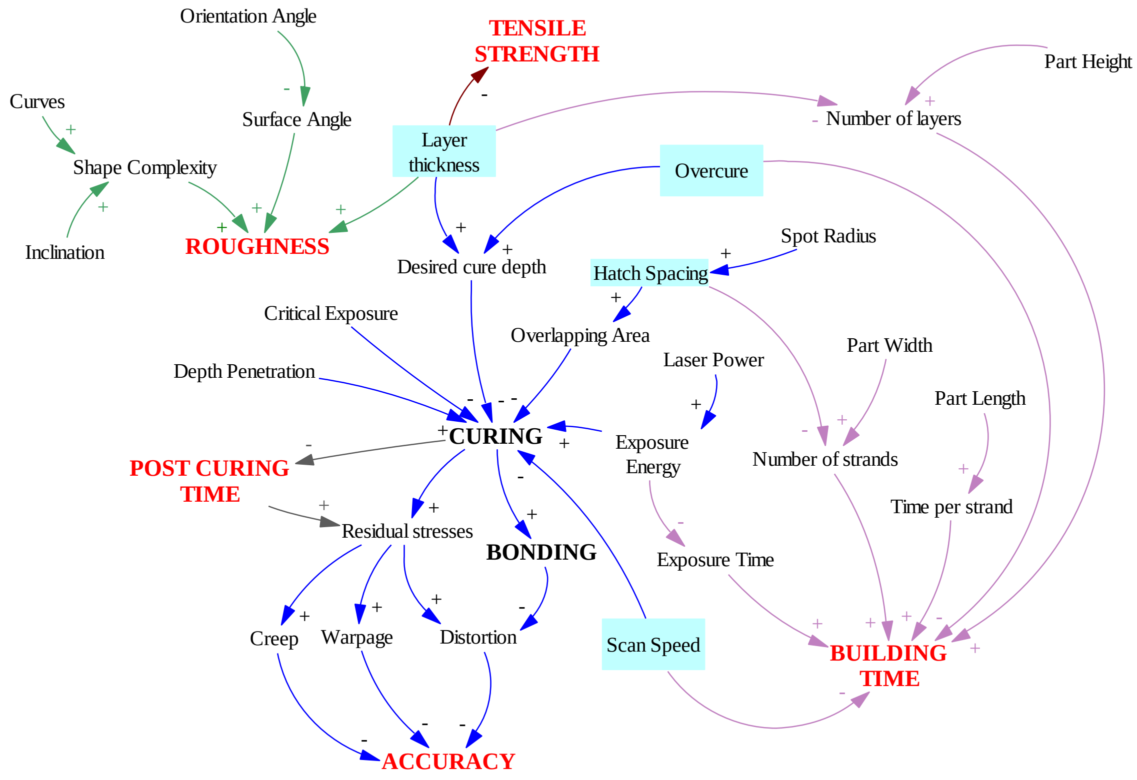


Figure 3-24: Conflicts of process parameters.

3.3.1 Layer Thickness

Layer thickness affects four different responses; roughness, tensile strength, building time, and accuracy. A small layer thickness is desirable for part good surface finish and high tensile strength; however, this will increase the number of layers needed to build the part and will ultimately increase the required building time, which are both undesirable.

Furthermore, smaller layer thicknesses will observe a small strand cure depth which require smaller amount of exposure energy resulting in better part curing, improved bonding, and reduced residual stresses; the thing that lead to good part dimensional accuracy, which is again desirable.

3.3.2 Over-cure

Over-cure is the second SL process parameter that affects two different responses in different ways; where, a small over-cure results in better part curing, improved bonding, and reduced residual stresses, which is desirable for part good dimensional accuracy. However, this will increase the part building time.

3.3.3 Spot Radius

Spot radius directly affects the hatch spacing, which in turn affects the dimensional accuracy of the produced part and the part building time. The use of small spot radius results in a small hatch spacing that will produce a more compactly cured structure, presenting smaller regions of uncured resin; thus, bonding between strands will increase resulting in good part accuracy; however, that again will require more building time.

On the contrary, a large hatch spacing will result in large overlapping area, with large un-cured region between the two parallel hatch lines; therefore, lowering the bonding between the hatch lines and resulting in part distortion and poor accuracy but it will also reduce the time required to build the part.

3.3.4 Scan Speed

The fourth and final process parameter that has conflicting effect on responses is the laser scan speed. A fast scan speed reduces the part building time but the part will not be fully cured thus long post-curing process will be needed that will increase the total completion time, affect some of the mechanical properties, and cause residual stresses leading to poor part accuracy as mentioned before.

It should be mentioned that in the case of fast scan speed, the laser power should be increased to obtain a sufficient amount of exposure energy to cure the part and also the hatch spacing should be decreased.

To conclude, CLDs succeeded to show the interrelationships between the different SL parameters and different responses. However, CLD cannot capture by how much these variables increased or decreased. Thus, Stock and flow variables are needed to capture the dynamic nature of some of the variables modelled in the CLD. Transition from CLD to SFDs will be illustrated step by step in the next chapter.

C h a p t e r   F o u r

4 QUANTITATIVE MODEL DEVELOPMENT

In this chapter, a quantitative model is developed by converting some variables in the CLD that has a potential to change with time into stock and flow variables. Then, mathematical equations and different values of input parameters are introduced to the model in order to capture its dynamic nature.

4.1 STOCK AND FLOW DIAGRAM

CLD are useful in many situations and are well suited to represent interdependencies and feedback processes. However, CLD suffer from a number of limitations. One of the most important limitations of causal diagrams is their inability to capture, if a component increases or decreases due its causal variable, by how much it changed and at which rate it did. Thus, Stocks and flows are the concepts that account for such quantities.

Stock and flow diagram (SFD) illustrates quantitatively the interrelation between the variables, and what causes them to change within the time. It also can provide a basis for simulating the behaviour of the system over time.

4.1.1 SFD Notations

The structure of the SFD is composed of five different components which are Stocks, Flows, valves, sources and sinks as shown below in Figure 4-1. Each component is described below in Table 4-1.

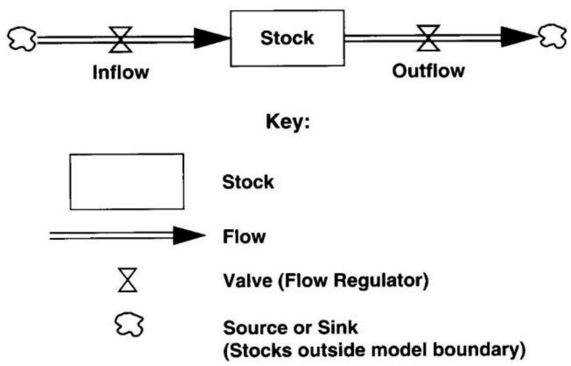
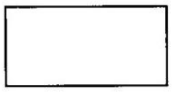


Figure 4-1: Stock and flow diagram notations.

Table 4-1: Stock and flow diagram components.

Notation	**Description**
	Stocks, also known as levels or accumulations. Stocks are drawn with rectangles. They change their value continuously over time with the given flows.
	Flows, also known as rates. Flow is drawn with an arrow.
	Valve, denoting the flow regulator (control the flows) is drawn at the middle of the arrow.
	Cloud represents either source or sink for the flows. A Source represents the stock from which a flow originating outside the boundary of the model arises. A Sink represents the stocks into which flows leaving the model boundary drain.

4.1.2 Mathematical Representation of Stocks and Flows

As mentioned before the SFD can quantitatively describes the interrelation between the variables but this act cannot be done without using mathematical equations [91].

Inflow indicates the increasing amount in the stock. On the other hand, outflow decreases the quantity in the stock. Therefore, inflow and outflow are positive and negative, respectively. Since there is always quantity in the stock at the initial time, the equation above becomes the following:

$$\mathrm{Stock(t)} = \int_{\mathrm{t_0}}^{\mathrm{t}} [\mathrm{Inflow(s)} - \mathrm{Outflow(s)}]\mathrm{ds} + \mathrm{Stock(t_0)}$$

Where,

$Inflow(s)$: Represents the value of the inflow at any time s between the initial time t_0 and the current time t.

$Outflow(s)$: Represents the value of the outflow at any time s between the initial time t_0 and the current time t.

4.2 IDENTIFICATION OF STOCK AND FLOW VARIABLES

The two significant variables that can change with the time in the causal loop diagram developed in the previous chapter are the part curing and part building time. These two variables will be converted to stock and flows.

4.2.1 Curing

The laser beam cures the part point by point; although happening at extremely high speeds, the laser stops at each point for some time exposing the liquid resin to the laser beam to solidify it.

The laser exposure starts to increases till reaching E_c; where, at this point the liquid starts to solidify and turns into gel (gel point where exposure = critical exposure [18]); however, the laser exposure should still exceed a threshold value.

This value is obtained when the laser exposure energy is larger than E_c of the resin and is called E_{max}, which should be obtained in order to obtain an acceptable level of curing. As seen below in Figure 4-2 the cycle of energy exposure is repeated from point to point till finishing the whole part.

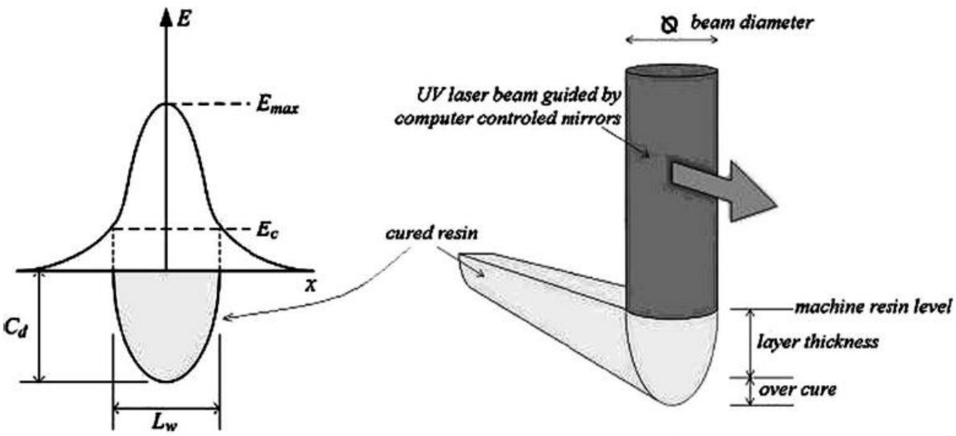


Figure 4-2: Bullet line shape [35]**.**

Figure 4-3 shows the exposure stock and flow diagram. The Actual Exposure is the stock variable, which represents the current amount of energy at a specific point on the part's surface. The inflow to the Actual Exposure is the Exposure Building Rate, which represents the rate of increase in exposure energy per unit time. Furthermore, the outflow in this model is the Rate of Decay, which represents the rate of decrease in exposure energy per unit time; reflecting that the laser beam has finished exposing a point of the resin and moved to another.

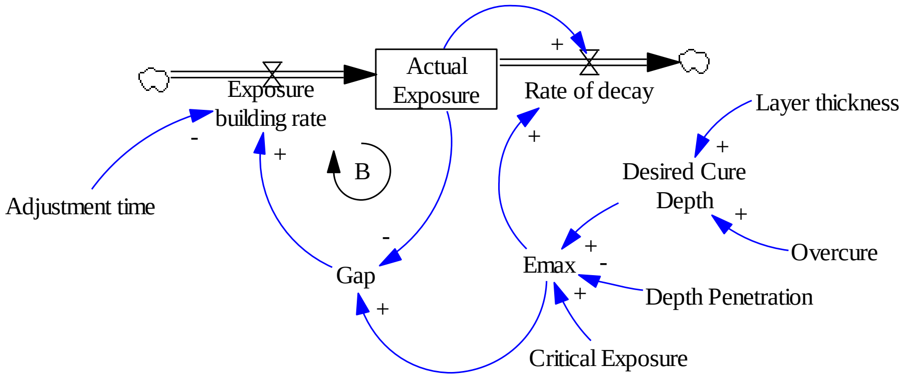


Figure 4-3: Exposure stock and flow.

The dynamics of the exposure relies on a balanced feedback loop that exists in this SFD. Where, if Actual Exposure is small (large), the Gap variable (representing the difference between the desired exposure energy (E_{max}) and Actual Exposure) will increase (decrease) and; hence, the Exposure Building Rate will increase (decrease) which in turn increases (decreases) the Actual Exposure stock. It should be noted that the Exposure Building Rate depends also on the Adjustment Time (inverse relationship), which is the time needed to fill the Gap.

This balanced feedback loop results in a behaviour that resembles the building process in reality. The actual exposure energy starts with a nominal exposure value resulting in a large Gap and leading to an increase in the exposure rate till it reaches the desired E_{max} value. The laser then moves to another point repeating the whole process of exposure. Since it moves to another point, the Rate of Decay acts on the Actual Exposure stock variable and reduces its value from E_{max} to the nominal exposure value once again (note the positive link between Rate of Decay and E_{max}); hence, representing another liquid point of resin that needs to be solidified.

Furthermore, it is clearly shown that the desired exposure (E_{max}) is influenced by many parameters like the resin depth penetration, resin critical exposure and the desired cure depth. Desired cure depth is also affected by layer thickness and over cure, as discussed in the previous chapter; where, this stock and flow diagram is still part of the larger CLD model that was developed earlier as seen in Figure 4-4.

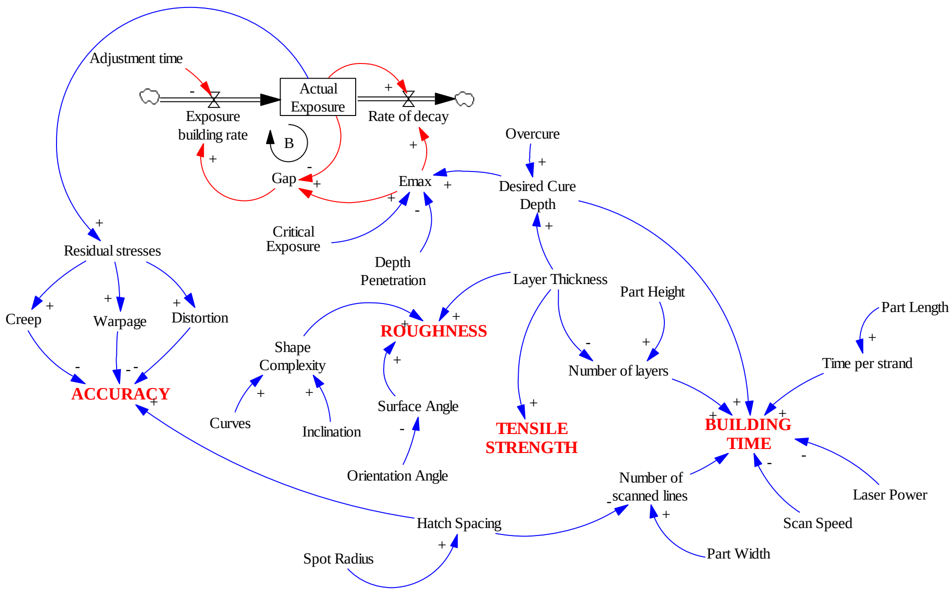


Figure 4-4: Exposure stock and flow in the model.

4.2.2 Building Time

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, which is rather different than what is reported by other researchers who base their analysis on the number of layers per built. This helps in identifying the different interrelationships between the variables and the responses and also helps in applying the model to any shape no matter how complex it is.

The developed SFD for the part building time is shown in Figure 4-5. The first stock variable is the Spot with Spot Building Rate as an inflow that represents the number of spots built per strand per unit time. This building rate is affected by the exposure time, which in turn is affected by the laser power as shown in the figure.

Strand building rate is the outflow of Spot stock and also the inflow to the Strand stock, which is the second stock variable. Whenever the number of spots reaches the desired number of spots per strand, this number is released from the Spot stock and transferred to the Strand stock denoting completion of one strand.

Similarly, Layer building rate is the outflow of the Strand stock and inflow of the Layer stock. Whenever the number of strands reaches the desired number of strands per layer, this number is released from the Strand stock and transferred to the Layer stock denoting completion of one layer.

Finally, Product building rate is the outflow of the Layer stock and inflow of the Product stock. Whenever the number of layers reaches the desired number of layers per product, this number is released from the Layer stock and transferred to the Product stock denoting completion of an entire product.

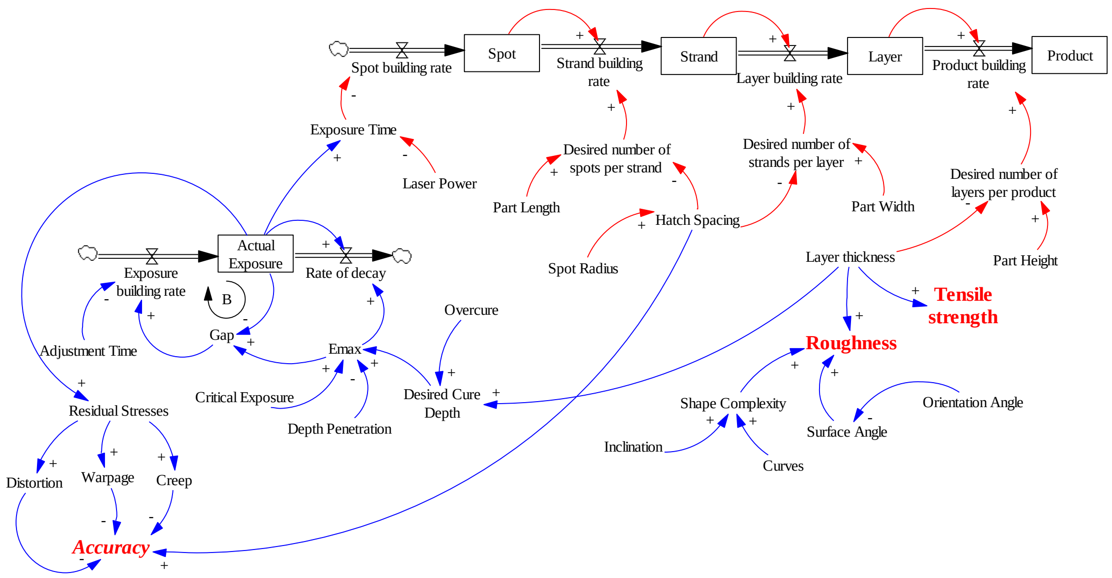


Figure 4-5: Building time stock and flow.

4.3 DEFINING VARIABLES AND THEIR MATHEMATICAL RELATIONSHIPS

Stock and flow along mathematical equations helped in simulating the building time. There are some steps are required before simulating the model.

4.3.1 Definition of Variables

Figure 4-6, shows the model that is used in simulating the building time and roughness. The variables and responses that are omitted from this model, such as accuracy and tensile strength, is mainly due to the absence of mathematical relationships in previous literature that relate the variables and responses to each other.

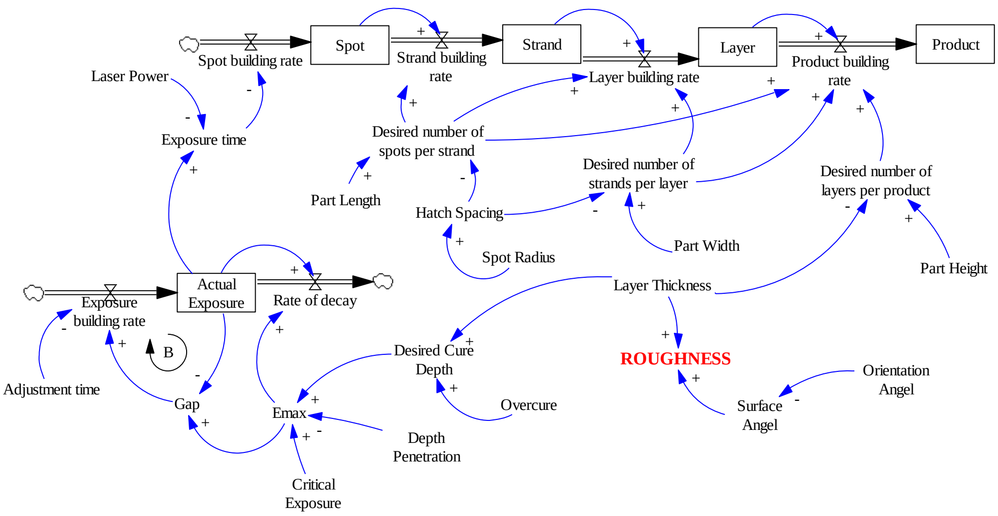


Figure 4-6: Model to be simulated.

4.3.2 Defining Mathematical Relationships

Entering mathematical equation to the Vensim software helps in predicting the building time and obtaining the surface roughness value.

Exposure

According to J. G. Zhou *et. al.* [34] the desired cure depth is equal to:

$$C_d = l_{th} + O_c \qquad \text{Equation 4-1}$$

According to the desired cure depth, the exposure energy is calculated. In order to be sure that the part is cured, the maximum exposure (E_{max}) must exceed the resin critical exposure. Both E_c *and* D_p are resin characteristics, which along with the Desired Cure Depth affect the E_{max} as shown in Figure 4-7.

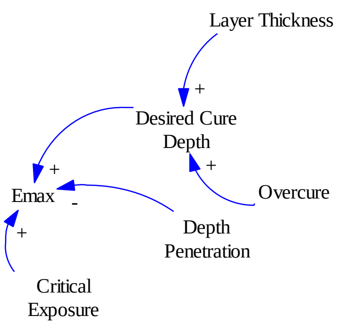


Figure 4-7: Variables affecting E_{max}.

These variables are identified in Vensim as "Causes" as shown in Figure 4-8 and are used to calculate E_{max} according to Equation 4-2 [48].

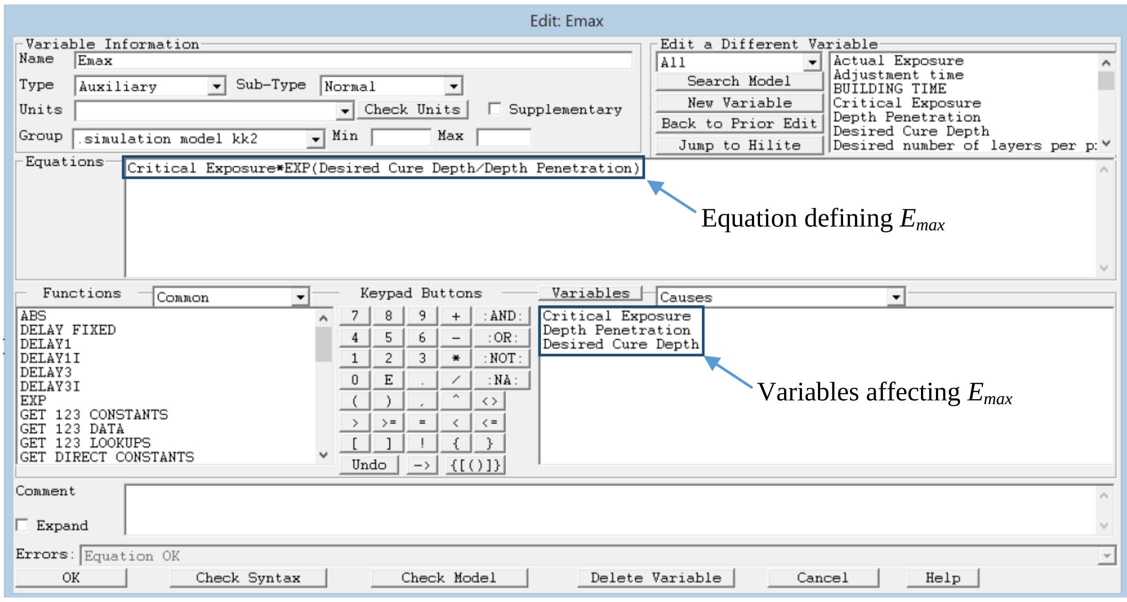


Figure 4-8: Defining equations of E_{max} in Vensim.

$$E_{max} = E_c * e^{C_d / D_p} \qquad \text{Equation 4-2}$$

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).

$$Gap = E_{max} - Actual\ Value \qquad \text{Equation 4-3}$$

The exposure building rate is equal to the amount of energy produced per unit time. The amount of energy produced to cover the gap. The unit time is the time of adjustment.

$$Exposure\ building\ rate = \frac{GAP}{Adjustment\ time} \qquad \text{Equation 4-4}$$

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 [110].

$$\text{Actual Exposure} = \text{Exposure building rate} - \text{Rate of decay} \qquad \text{Equation 4-5}$$

With initial value = 0

In order to achieve the maximum energy (E_{max}), a total exposure time is needed for each spot, which is equal to the actual exposure energy divided by the laser power [34].

$$\text{Exposure time} = \frac{\text{Actual Exposure}}{L_p} \qquad \text{Equation 4-6}$$

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

$$\text{Exposure time} = \frac{\text{MAX (Actual Exposure,m)}}{L_p} \qquad \text{Equation 4-7}$$

Building time

As the analysis of the building process focuses on the number of spots produced per built therefore, all the model stocks (spot, strand and layer) are actually stock of spots and all the model input flows and output flows are spots flows per seconds.

The spot building rate (spot input) is the inverse of the exposure time.

$$\text{Spot building rate} = \left(\frac{1}{\text{Exposure time}}\right) \qquad \text{Equation 4-8}$$

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

$$\text{Spot} = \text{INTEGER (MAX (Spot building rate, 0))} - \text{Strand building rate)} \qquad \text{Equation 4-9}$$

The hatch spacing is calculated based on Equation (10). K is a constant, generally near 2, so the optimum hatch spacing is of the order of the beam diameter [48, 110].

$$\text{HS} = \text{K} * \text{W}_\text{o} \qquad \text{Equation 4-10}$$

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

$$\text{umber of spots per strand} = \text{INTEGER} \left(\frac{\text{Part Length}}{\text{H}_\text{s}}\right) \qquad \text{Equation 4-11}$$

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

$$Strand\ building\ rate = \begin{cases} Desired\ \ spots/strand\ ; if\ Spots \geq Desired\ spots/strand \\ 0 \end{cases}$$ Equation 4-12

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

$$\text{Strand} = \text{Strand building rate} - \text{Layer building rate}$$ Equation 4-13

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

$$\text{Number of strands per layer} = \text{INTEGER}(\text{Width of part}/\text{H}_\text{s})$$ Equation 4-14

Layer building rate (strand output) is equal to the number of spots needed to build a single layer.

$$\text{Layer building rate} = \begin{cases} \frac{spots}{strand} * \frac{strands}{layer} ; if\ spots \geq \frac{spots}{strand} * \frac{strands}{layer} \\ 0 \end{cases}$$ Equation 4-15

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

$$\text{Layer} = \text{Layer building rate} - \text{Product building rate}$$ Equation 4-16

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

$$\text{Number of layers per product} = \text{INTEGER}\ (\text{Part Height}\ /\text{L}_{\text{th}})$$ Equation 4-17

Product building rate (layer output) is equal to the number of spots needed to build a single product.

$$Product\ Building\ rate = \begin{cases} \frac{layer}{product} * \frac{strand}{layer} * \frac{spot}{strand} ; if\ spots \geq \frac{layer}{product} * \frac{strand}{layer} * \frac{spot}{strand} \\ 0 \end{cases}$$ Equation 4-18

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

$$\text{Product} = \text{Product building rate} \qquad \text{Equation 4-19}$$

Roughness

The summation of both the surface angle and the orientation angle is equal to 90. Therefore, the surface angle is equal to

$$\theta_N = 90 - \theta \qquad \text{Equation 4-20}$$

SLA cured shape can be quantified with one of the surface finish parameters such as surface roughness or cusp height. It is possible to express the cusp height as a relationship between the angle of the build, and the layer thickness that is used [39, 50].

$$Roughness = L_{th} * \cos\theta_N \qquad \text{Equation 4-21}$$

4.4 MODEL VERIFICATION AND VALIDATION

4.4.1 Verification

Verification is the process of ensuring that the model behaves in the way it was intended. In this section three tests were made to verify the model. First testing the equations, in more details this test checks whether each equation in the model dimensionally corresponds to the real system or not. As an example, the $E_{\max}$ equation which showed 0.368 mJ/mm^2 as seen in the equation below. Figure 4-9 shows that the model output value (vensim software output) is consistent with the calculated equations below.

$$E_{\max} = E_c * e^{C_d/D_p} = 0.109 * e^{0.17/0.1397} = 0.368$$

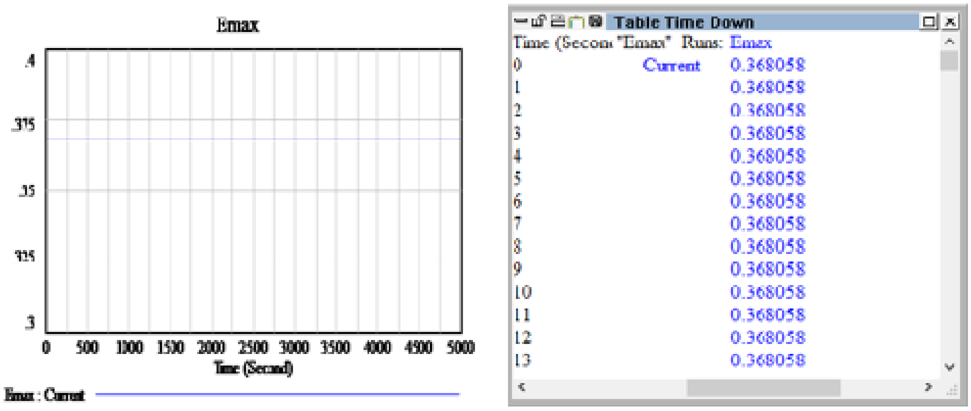


Figure 4-9: $E_{\max}$ model output value

Secondly Extreme-conditions test, whether the model exhibits a logical behaviour when selected parameters are assigned extreme values or not. Two extremes condition tests were made, one with extremely low laser power value and the other with extremely high laser power value.

Figure 4-10 shows the first extreme condition test output using a laser power with 100 mW. The simulation results of the product resulted out only one product that was built with the given setup time (5000 seconds).

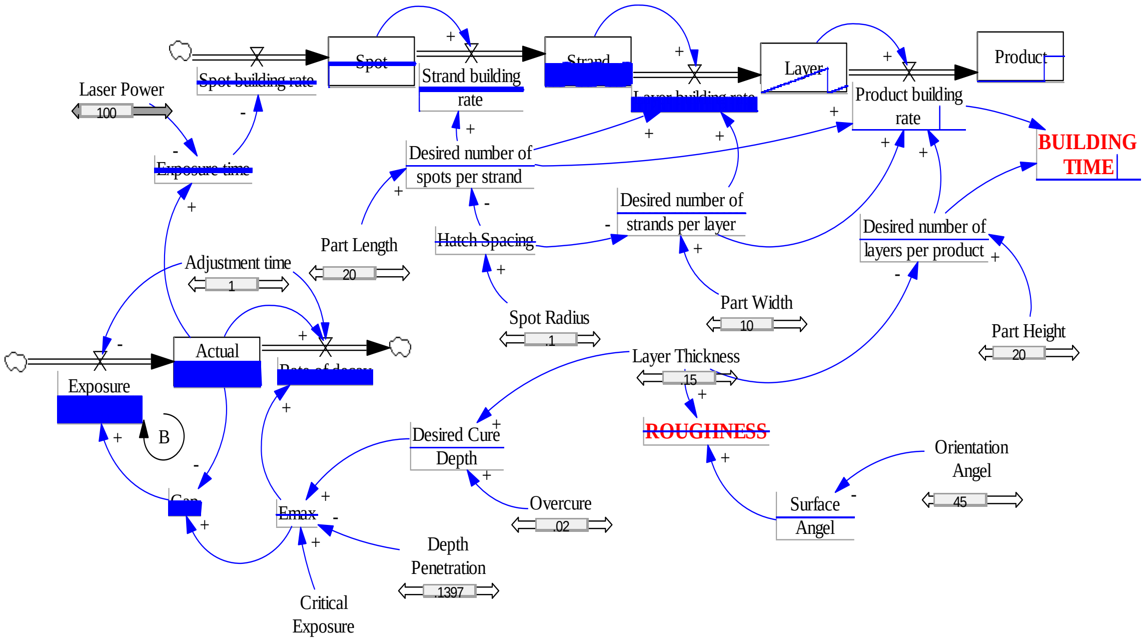


Figure 4-10: Extreme condition test output with 100wM laser power

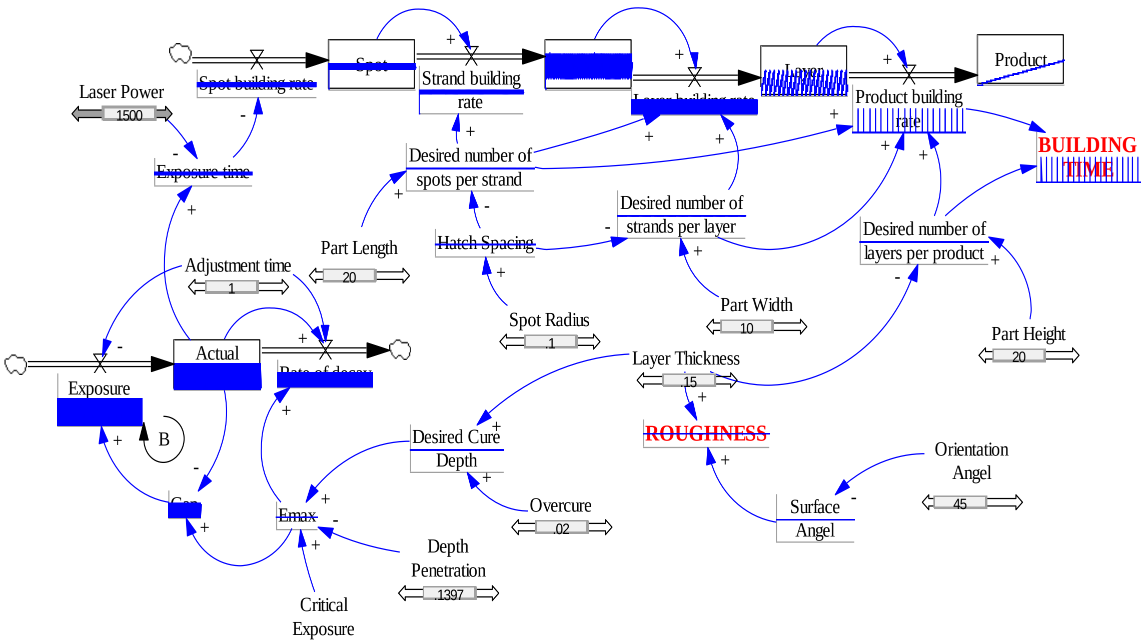


Figure 4-11: Extreme condition test output with 1500wM laser power

Figure 4-11 shows the second extreme condition test output using a laser power with 1500 mW. The simulation results of the product showed that more than one product will be built with the same set up time. It can be concluded that the model respond to the extreme conditions.

Thirdly the causes and effects testing, whether the model respond to the causes or not? As the layer thickness value is affected by three other factors, this parameter will be tested according to the cause and effect test. Figure 4-12 shows that the layer thickness is equal to the multiplication of (the desired number of spots per strands * the desired number of strands per layer * desired number of layer per product) which are constant values according to the part dimensions. Therefore the layer thickness value in the model was affected by the three factors which means that the model respond to show the causes and effects of the parameters.

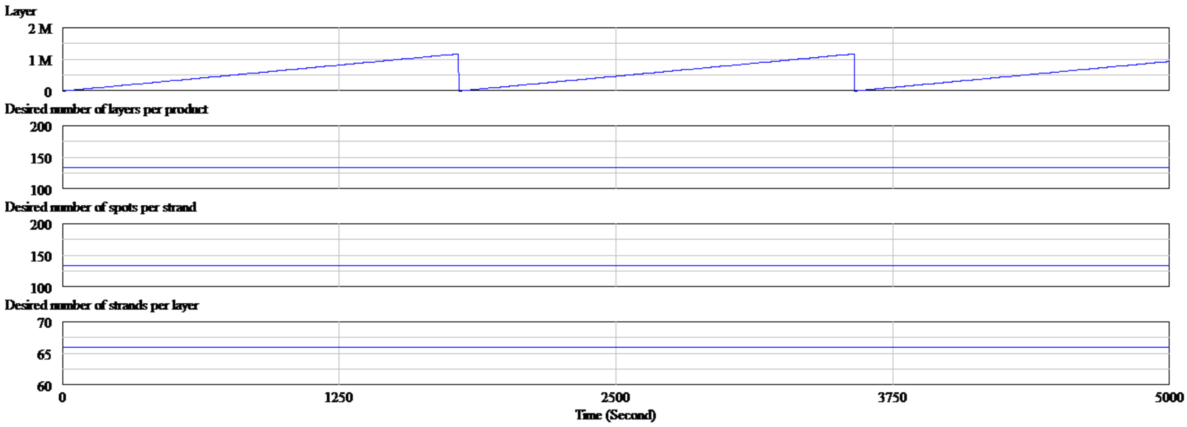


Figure 4-12: cause and effect verification test

4.4.2 Model validation

Validation is the process of ensuring that whether the conceptual simulation model is an accurate representation of the system under study or not. This was be made by two test which are the behaviour validity test and Structure validity test.

First the behaviour validity test which shows how well model-generated behaviour matches observed behaviour of the real system. This will be shown in the chapter five, the exposure stock results is nearly like theoretical curve as will be illustrated in 5.3.1. Moreover, changing a parameter and seeing its effect on the building time was actually like what found in literature as will be seen in 5.4 and 5.5.

2. Structure-verification test: Compare the structure of a model with structure of the real system. Actually the structure of the system was build based on equations found in literature as was discussed in chapter 3.

Chapter Five

5 EXPERIMENTATIONS, RESULTS, AND ANALYSIS

5.1 MODEL SETUP

Specifying the starting time, the ending time, the time-step, and the time units are firstly required in Vensim. The initial time is set to zero, final time is 5,000, time step = 1 and all units are in seconds. The selected final time was enough to cover the building time of more than one part.

5.2 MODEL INPUTS

To test the developed model, a rectangular part was chosen with dimensions $20mm \times 10mm \times 20mm$ as illustrated in Figure 5-1. The SL 5000 machine is used with $L_p = 216\, mW$, Beam diameter = 0.20 – 0.30 mm and $L_{th} = 0.15\, mm$. The material used is SL7510 Resin, which is commonly used with the SLA 5000 with $E_C = 0.109\ mJ/mm^2$ and $D_p = 5.5\, mm$. According to the machine and Resin specification $O_c = 0.02\, mm$ (Table 5-1 lists all model input values).

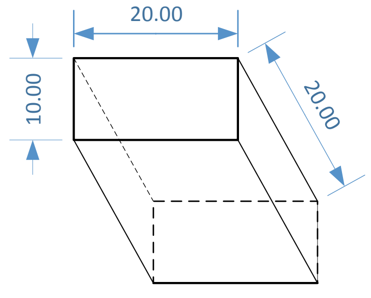


Figure 5-1: Part shape and dimensions.

Table 5-1: Model inputs.

Process parameters	W_o	D_p	Adj. time	M	K	θ
Value	0.1 mm	0.1397 mm	1 sec.	0.36 mJ/mm^2	1.5	45

5.3 RESULTS AND ANALYSIS

The simulation results of the Vensim software are in form of graphs. Two stocks graphs are clarified below. Then, the effect of changing the process parameters values in the model is illustrated. After that, different simulation runs were made with different parameters value and were graphically shown. Finally, empirical relationships were developed.

5.3.1 Exposure stock graph

Figure 5-2 shows the Exposure energy (mJ/mm^2) versus the part building time in seconds. It is seen that the exposure value starts with zero value and increases till reaching the $E_{\max}$ (the desired value to obtain solidification), after that the exposure decrease to reach its original value. This cycle is repeated until building all the part. The cycle was shown above in Figure 4-2.

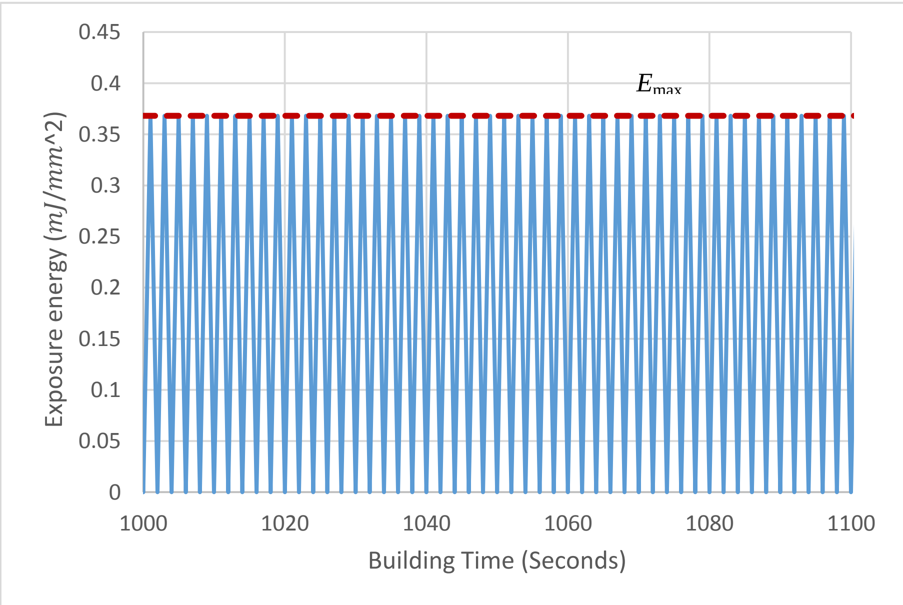


Figure 5-2: Stock Exposure graph.

5.3.2 Spot and strand stock graph

Figure 5-3 shows the number of spots versus the building time in seconds for both the spot and strand stock. It is clearly seen that the magnitude of the number of spots in the spot stock is greater than that of the strand stock, and that because the strand requires a greater number of spots.

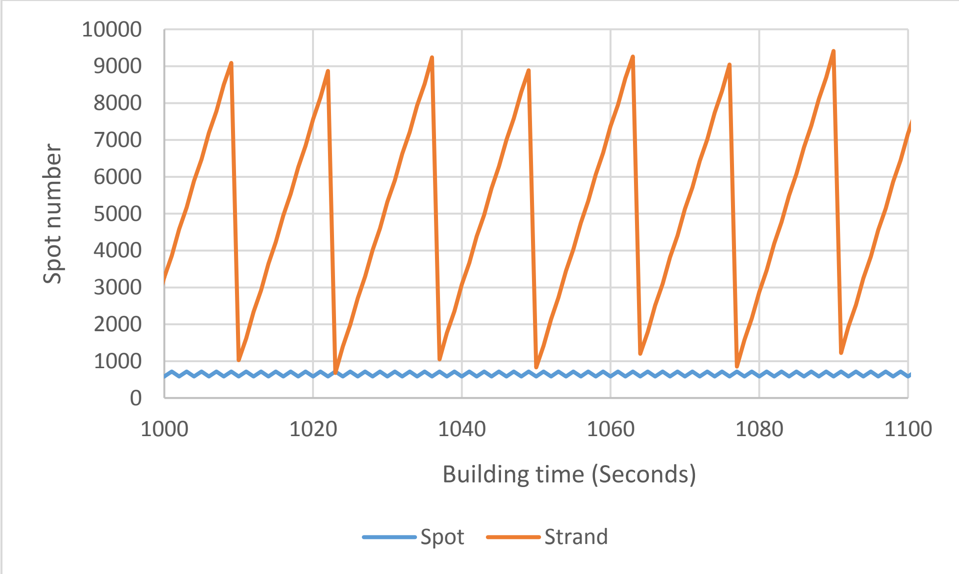


Figure 5-3: Spot and strand stock graph.

5.3.3 Layer stock Graph

Figure 5-4 shows the layer stock graph, it shows how many spots needed to produce the required number of layer versus to the building time. The inclined line has small steps, each step represents a single layer till building the required number of layers to produce a single product. As seen in order to build the required number of layers, a 1.167 million spots are needed (produced). Whereas, the vertical line shows that the required number of layers ended up after 1,789 seconds.

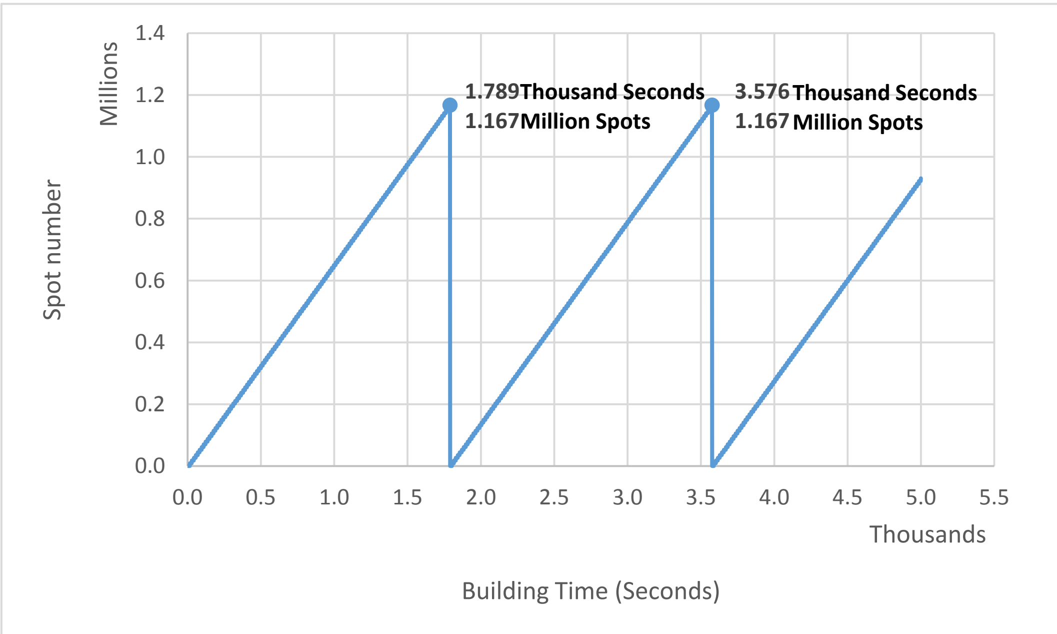


Figure 5-4: Layer stock graph.

5.3.4 The Product stock Graph

Figure 5-5 shows the product stock graph, each step in the figure represents a final product which took about 1790 seconds (almost half an hour). As the product is composed of specific number of layers, therefore 1,167,474 spots are also needed to produce a single product.

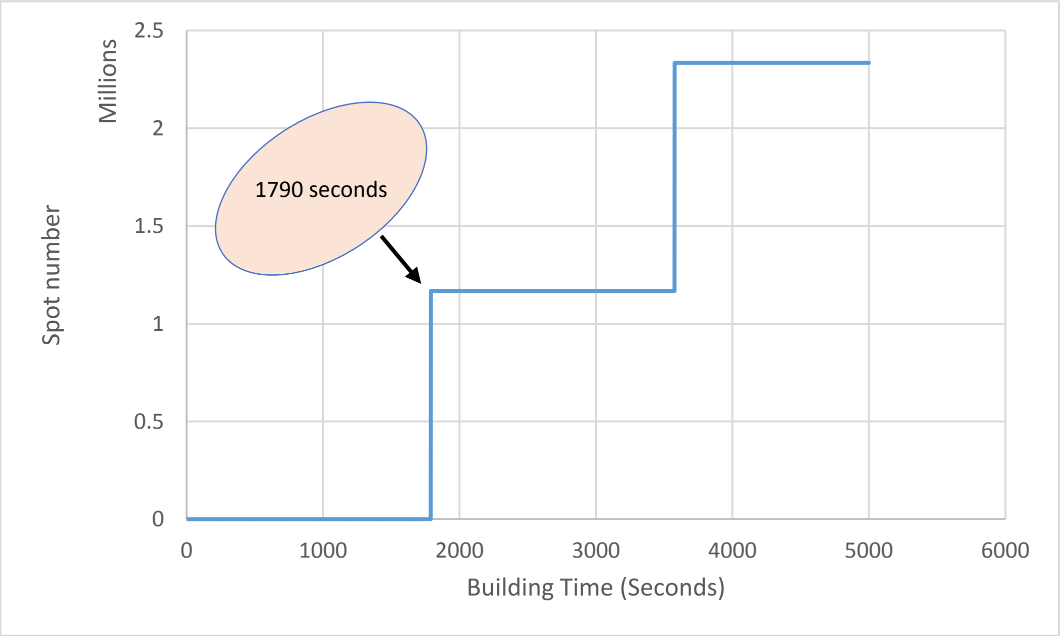


Figure 5-5 : Product stock graph.

5.4 EFFECT OF CHANGING A SINGLE PARAMETER ON THE SL PROCESS

In this section, the effect of changing the laser power from 216 mW to 160 mW is shown in Figure 5-6. It took about 2416 seconds (almost 40 minutes) to build a single product which is equal to 1,167,474 spots. While, with 216 mW the building time was 1790 seconds (almost half an hour). Thus, it can be concluded that as the laser power decreases the part building time increases “negative polarity”.

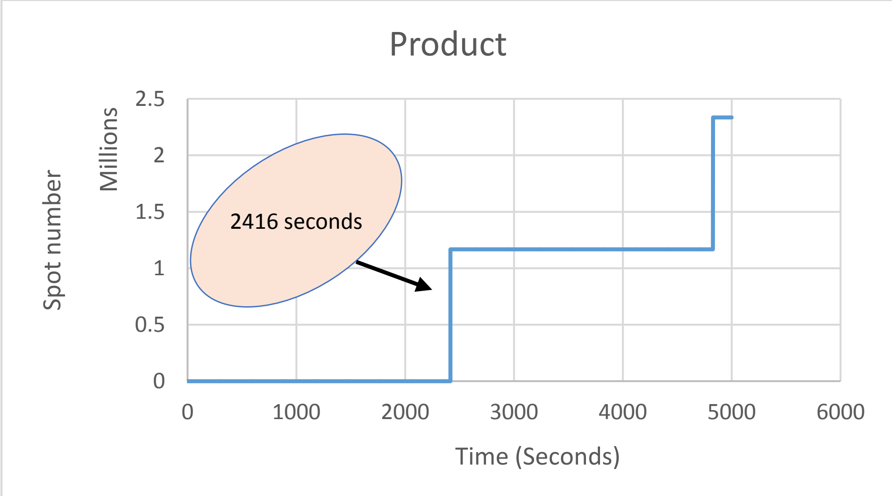


Figure 5-6: Product stock with different value of laser power.

5.5 EMPIRICAL RELATIONSHIPS

Different input parameters (According to the SLA 5000 appendix D) values were added to the model and simulated. While the other parameters were fixed as used in section 5.2. From the results, graphs were drawn and empirical relationships were observed with the correlation.

5.5.1 Layer Thickness Graph

Figure 5-7 shows how different input values of the layer thickness affects both the building time and surface roughness.

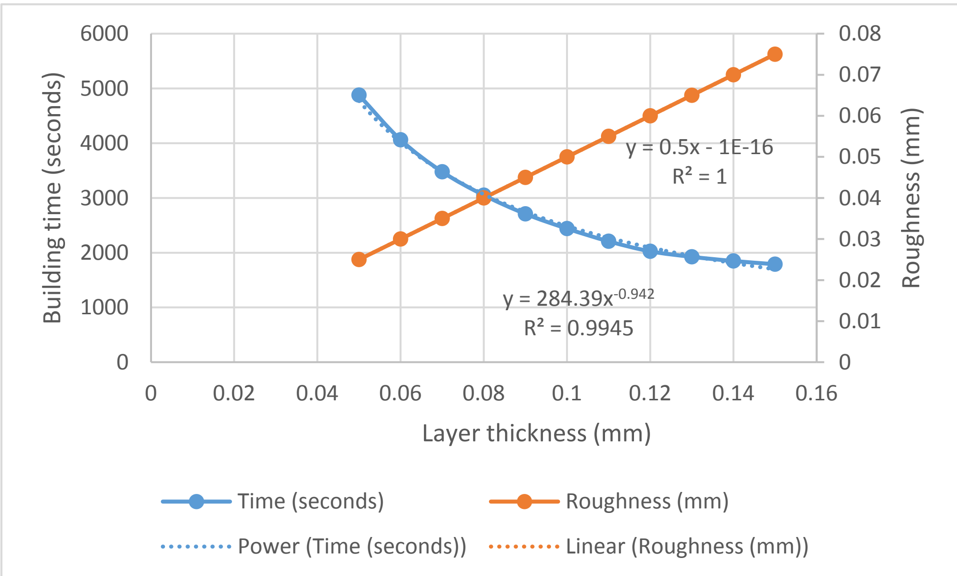


Figure 5-7: Layer thickness graph.

The graph clearly shows that when the layer thickness increases the surface roughness increases too, while the building time decreases. Then, two empirical relationships were developed between the two responses and the layer thickness. Table 5-2 shows that a power trend line has the highest correlation which is equal to “0.9945”.

Table 5-2: Building time versus layer thickness.

Regression	Exponential	Linear	Logarithmic	Polynomial	Power
Correlation	0.9534	0.8847	0.9625	0.9942	0.9945

$$\boldsymbol{Building\ time\ =\ 284.39\ L_{th}{}^{-0.942}}$$

While it is clearly shown that the surface roughness has linear trend line was with a correlation “1”.

$$\boldsymbol{Roughness = 0.5\ L_{th}}$$

5.5.2 Laser Power Graph

Figure 5-8 shows how different input values of the laser power affects both building time and the exposure time. It is clearly seen that when the laser power increases both the building time and exposure time decreases. Then, two empirical relationships were developed between the two responses and the laser power.

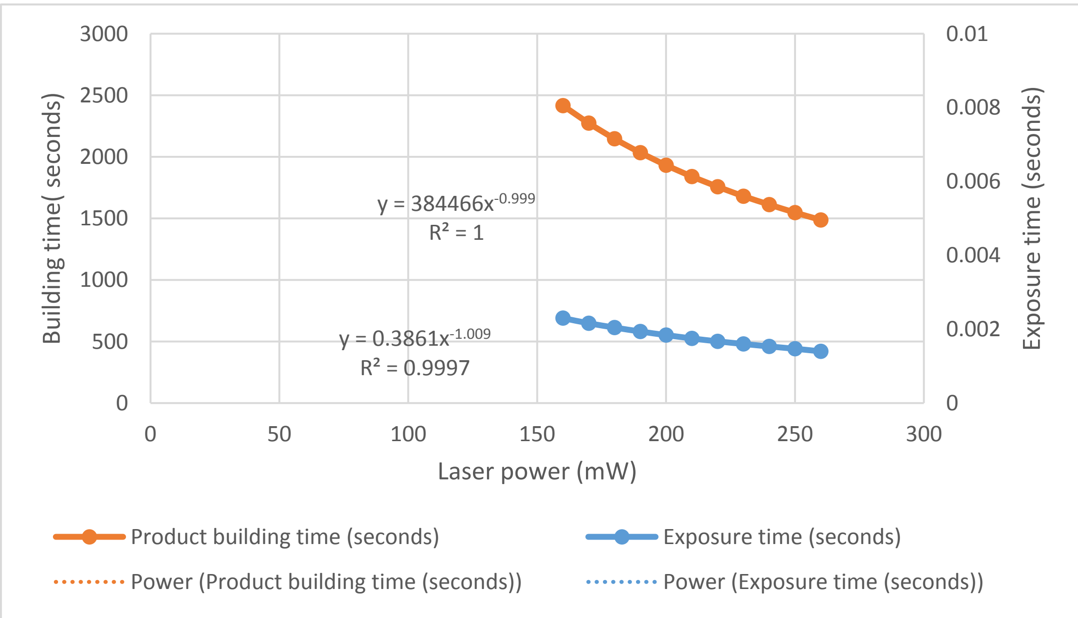


Figure 5-8 : Laser power graph.

Table 5-3 shows that a power trend line has the highest correlation which is equal to "1". While, Table 5-4 shows that a power trend line has the highest correlation which is equal to "0.9997".

Table 5-3: Building time versus laser power.

Regression	Exponential	Linear	Logarithmic	Polynomial	Power
Correlation	0.9952	0.9814	0.9952	0.9997	1

Table 5-4: Exposure time versus laser power.

Regression	Exponential	Linear	Logarithmic	Polynomial	Power
Correlation	0.9965	0.9837	0.9962	0.9993	0.9997

Hence, the empirical formulae for the building time and exposure time are as follows: $\boldsymbol{Building\ time = 384466\ L_p{}^{-0.999}}$ and $\boldsymbol{Exposure\ time = 0.3861e^{-1.009\ L_P}}$.

5.5.3 The Beam Spot Radius

Laser (beam) spot size in SLA 5000 has a finite range as seen in Appendix D, these values are simulated with a step of 0.05 mm. Figure 5-9, shows how different input values of the beam spot radius affects both building time and the desired number of strands per layer.

It is seen from the graph on the next page that when the beam spot radius size increases both the building time and the desired number of strands per layer decrease. Then, two empirical relationships were developed between the two responses and the spot radius. Table 5-5 shows that a power trend line has the highest correlation which is equal to "0.9999". Hence, $\boldsymbol{Desired\ number\ of\ strands\ per\ layer\ = 13.12w_o{}^{-1.005}}$.

Table 5-5: Desired number of stands per layer versus spot radius size.

Regression	Exponential	Linear	Logarithmic	Polynomial	Power
Correlation	0.985	0.936	0.9852	0.9973	0.9999

Furthermore, Figure 5-9 shows that a power trend line has the highest correlation which is equal to "1" resulting in the following formula: $Building\ time = 17.482\ w_o{}^{-2.01}$

Table 5-6: Building time versus spot radius size.

Regression	Exponential	Linear	Logarithmic	Polynomial	Power
Correlation	0.9825	0.8649	0.942	0.992	1

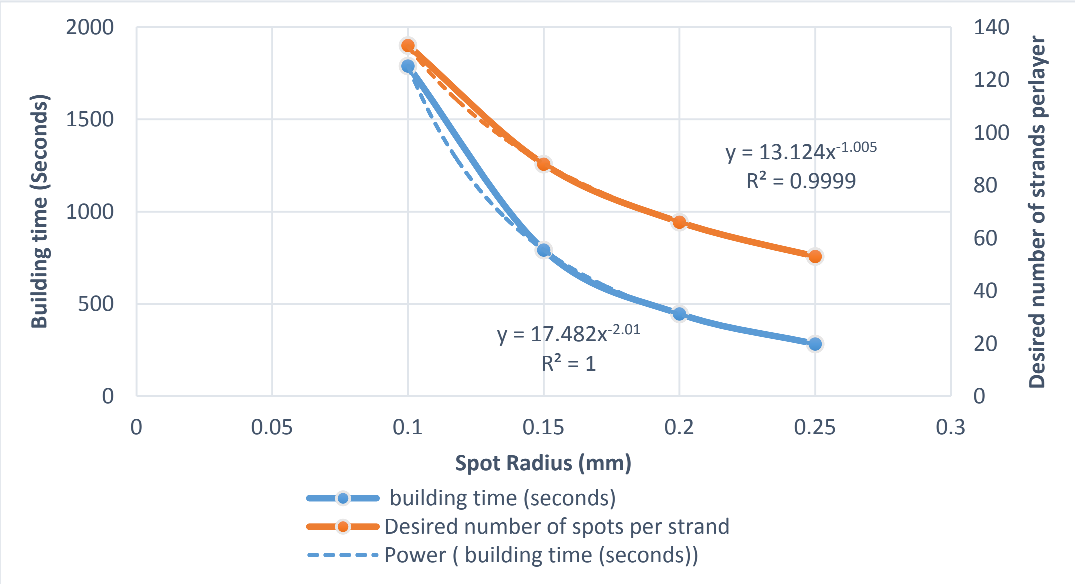


Figure 5-9: Beam spot radius.

5.5.4 The surface Angle

Figure 5-10 shows how different input values of the surface angle affects the roughness "cusp height". It is clearly seen that when the surface angle increases the roughness "cusp height" decreases.

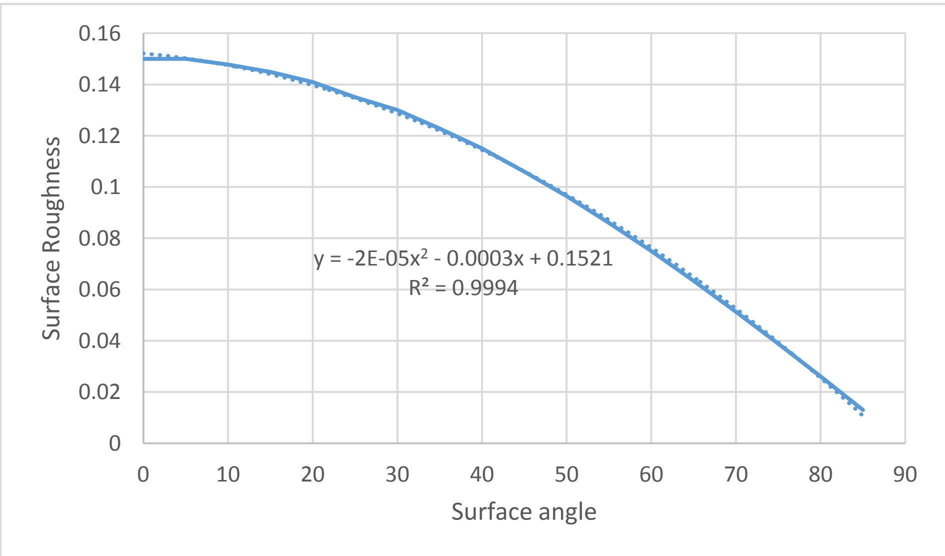


Figure 5-10: Surface angle

Table 5-7 shows that a polynomial trend line has the highest correlation which is equal to “0.9994”; resulting in the following empirical formula:

$$\text{Roughness} = -0.00005\,\theta_N{}^2 + 0.003\theta_N - 0.1521$$

Table 5-7: Orientation angle versus roughness

Regression	Exponential	Linear	Polynomial
Correlation	0.785	0.9523	0.9994

5.6 SUMMARY

It is seen that the SD approach helped in developing empirical relationships between different parameters and responses; these are summarized in Table 5-8.

Table 5-8: Summary of the empirical relationships developed.

Cause	**Effect**	**Empirical Relationship**
Layer thickness	Building time	$Building\ time = 284.39\,L_{th}{}^{-0.942}$
Layer thickness	Roughness	$Roughness = 0.5\,L_{th}$
Laser power	Exposure time	$Exposure\ time = 0.3861e^{-1.009\,L_P}$
Laser power	Building time	$Building\ time = 384466\,L_p{}^{-0.999}$
Beam spot radius	Building time	$Building\ time = 17.482\,w_o{}^{-2.01}$
Surface angle	Roughness	$Roughness = -0.00005\,\theta_N\ 2 + 0.003\theta_N - 0.1521$

Chapter Six

6 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

6.1 CONCLUSIONS

Conclusions drawn from this work are:

1. Modelling stereolithography by using system dynamic approach is a novel methodology used in the AM field.
2. The Qualitative model has shown to be very useful in understanding the interactions between the building parameters and finding the interrelationships between them.
3. The Qualitative model succeeded to show the different effects that a parameter can have on the responses.
4. The Quantitative model investigated the effect of various parameters on part building time and can be effectively used for predicting the building time of different products (sizes, materials…) and machine specifications such as (laser power, spot radius…).
5. The Quantitative model helped in developing empirical relationships between parameters and responses that were not addressed in literature.

6.2 RECOMMENDATIONS FOR FUTURE WORK

It is recommended that further research shall be undertaken to

1. Model other AM processes such as (SLS, FDM and EBM) using SD approach.
2. Conducting experiments for getting relationships between the exciting process parameters and other responses such as (dimensional accuracy, tensile strength, compressive strength and hardness) that were not found in literature.

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APPENDICES

Appendix A: Publication Arising from This Work

Appendix B: Additive Manufacturing Processes Classification

Appendix C: Analysis of SL Process Parameters Literature Review

Appendix D: SLA 5000 System