AC 2011-2162: RET PROJECT IN ADDITIVE MANUFACTURING

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RET Project in Additive Manufacturing

1. Abstract

Working in an emerging science, technology, engineering and math (STEM) research field, finding new results or contributing to a knowledge set, and finally going back to deliver these findings to your K12 students are important for the 21^{st} century's technological advancement. The additive manufacturing project reported in this paper is a part of National Science Foundation (NSF) grant that provides funding for a 3 year continuing award to support a Research Experiences for Teachers (RET) in Engineering Site program at the Tennessee Technological University (TTU) entitled, "RET Site: Research Experience for Teachers in Manufacturing for Competitiveness in the United States (RETainUS)". One of the RET research projects accomplished by the project team and one high school math teacher was on the generation of knowledge-base for the 3D printing end-users. Analytical and experimental studies were performed using the 3D printing software and equipment located at the Remotely Accessible Rapid Prototyping Laboratory of Tennessee Tech University (TTU). The objective of this research was to generate a set of new information so that manufacturing engineering/technology educators and practitioners access and use it in their daily lectures/operations. The findings of the summer research study and its implementation in a manufacturing course are reported in this paper.

2. Introduction

RETainUS program contributes to advancing the manufacturing base in the U.S. through meaningful changes in the teachers' understanding of manufacturing and how it relates to the Math and Science curriculum. This program aims at improving the teachers' comprehension of the research and development process through hands-on experience and real world problems that relate to: a) advancing the state of the art in conventional manufacturing processes; b) new trends in manufacturing such as rapid prototyping, c) emerging technologies such as nanomaterials and manufacturing of fuel cells and special coating materials, and d) enabling technologies serving manufacturing processes in general such as intelligent optimization. Special attention is given to counties and schools where minorities and underserved populations are concentrated. In addition to working with in-service teachers, RETainUS exposes pre-service teachers to the exciting world of engineering research and how to uniquely incorporate it into the learning environment.

The current additive manufacturing study was performed in 3D Printing field and a knowledge base was gathered, analyzed, and developed for the end-users of the 3D Printing. Experimental data was gathered for the weights of objects, estimated time versus experimental time, binder usage, layer thickness versus time, location in the production tray versus time, orientation versus time, scaling down versus time and surface area to volume ratio versus time. The results were presented as a poster presentation at the end of the program. Performed research was evaluated by the external judges and the center for manufacturing research.

The current ASEE paper reports the detailed RET additive manufacturing study and its beta testing results in an educational setting.

3. Background

NSF's RET program supports the active involvement of K-12 STEM teachers and community college faculty in engineering research in order to bring knowledge of engineering, computer science, and technological innovation into their classrooms. The goal is to help build long-term collaborative partnerships between K-12 STEM teachers, community college faculty, and the NSF university research community by involving the teachers and community college faculty in engineering and computer science research and helping them translate their research experiences and new knowledge into classroom activities. Partnerships with inner city schools or other high needs schools are especially encouraged, as is participation by underrepresented minorities, women, and persons with disabilities. This program features two mechanisms for support of in-service and pre-service K-12 STEM teachers and community college faculty: RET supplements to ongoing engineering awards and new RET Site awards. RET supplements may be included in proposals for new or renewed NSF Directorate for Engineering grants or as supplements to ongoing NSF engineering funded projects. RET Sites are based on independent proposals from engineering or computer and information science departments, schools or colleges to initiate and conduct research participation projects for a number of K-12 STEM teachers and/or community college faculty. This current educational research study was performed in summer 2010 as parts of an NSF RET project entitled RET *Site: Research Experience for Teachers in Manufacturing for Competitiveness in the United States (RETainUS)"*.

NSF's Course, Curriculum, and Laboratory Improvement (CCLI) program (now, called as TUES) seeks to improve the quality of STEM education for all undergraduate students. The program supports efforts to create, adapt, and disseminate new learning materials and teaching strategies, develop faculty expertise, implement educational innovations, assess learning and evaluate innovations, and conduct research on STEM teaching and learning. The program supports three types of projects representing three different phases of development, ranging from small, exploratory investigations to large, comprehensive projects. The RET educational research study performed in this paper has been conducted at TTU's *Remotely Accessible Rapid Prototyping Laboratory which was established via NSF's CCLI program funds*.

3D printing is a relatively new manufacturing technology patented by Massachusetts Institute of Technology in 1993. This technology utilizes an additive technique to create a three-dimensional object from a digital, two-dimensional drawing. The benefit of this technology is that it can "compress the design cycle, generate new concepts, communicate clearly, faster collaboration, and reduce errors."[1] The object is created by slicing the drawing into layers. The machine works much like an inkjet printer laying down a fine layer (0.0035 inches to 0.004 inches) of powder followed by a layer of adhesive binder. This process is continued layer by layer until the object is complete. The 3D printing machine can easily produce a colored part using its cartridges, binder and powder. The software is capable of scaling an object so the exact object may be printed in various sizes. "3D printing is able to make complex shapes as quickly as non-complex shapes."[2] This technology has revolutionized the rapid prototyping industry. It is now the most commonly used method of rapid prototyping due to its relatively low cost and quick turn-around time. The limitations of this technology are the rough finish, tolerance and precision among the same objects printed at different times.[3] *Packaging Digest* suggests that by the year 2013 the 3D printing industry will grow to a $782.6 million market.[4-5]

This educational research study aims to establish a knowledge base for end-users of 3D printing technology. The ZCorp Z406 machine was used in this RET project. The objects analyzed range from a simple rectangular prism to a much more complicated prototype of a car. All objects were drawn, estimated, and printed in monochrome. All objects were analyzed one per run. In this paper the authors present their findings based on estimated and experimental data as it relates to time, orientation of the object, layer thickness, scale, and surface area to volume ratio.

4. Project Activities

RET Project in Additive Manufacturing has been conducted in six weeks during summer 2010. The majority of the study was conducted by Mrs. Lisa Choate, who is a mathematics teacher at Cannon County High School in Woodbury, Tennessee. Kenan Hatipoglu, who is a graduate research assistant at the Center for Manufacturing Research, helped and supported her research studies. Dr. Ismail Fidan, who is the project mentor, guided both teacher and graduate student in experimental and analytical additive manufacturing studies. Dr. Mohamed Abdelrahman managed the summer project in its RETainUS key deliverables. The project findings reported are the results of authors' collaborative efforts. The following list briefly reports the teacher's RET activities:

Week 1: Orientation, training and formulation of research question.

- Half-day orientation regarding available resources, campus facilities, campus security, laboratory safety rules, intellectual property issues, etc.
- Introduction by mentors to their research areas and possible research questions/opportunities.
- Training in research methodology for independent investigation:
    - Teachers work with their mentors and graduate students to understand and refine the research questions. The mentors guide the teachers to identify and understand the theories and references needed to investigate their questions.
    - Teachers develop a computer study and/or experimental measurement plan to address the research study question in consultation with their mentors.
- Identify possible curriculum links of the study question and create a presentation of the plan to peers and mentors by the end of first week.

Weeks 2 – 6: Research Study

- Conduct the research study according to plans developed in Week 1.
- Meet once per week with the full group to review progress with peers.
- Meet twice per week within subgroups working on related research questions.
- Document changes in research plans as needed. Initiate and document plans for development of curriculum learning module in consultation with mentor and engineering research and development consultants.

Curriculum Learning Module Implementation:

During the summer RET program, teachers develop a curriculum learning module based on their research experience and state curriculum standards. Learning modules is based on the Legacy Cycle format. A one-day Legacy Cycle workshop is conducted to provide the framework for teachers to develop their instructional materials. Each teacher has an equipment mini-grant of $2,000 to spend on resources and equipment to aid in the delivery and implementation of their modules in their classrooms.

To support teachers in the classroom, they are enrolled in a special topics graduate course (1 credit hour – offered by TTU – Tuition-free) in the Fall following the summer institute. To earn credit in the course, participants develop their Legacy Cycle module, submit it for feedback, and revise accordingly. Teachers then teach their module and write a reflection outlining (a) successful/unsuccessful aspects of their module and (b) students' performance, reactions, and learning resulting from the module.

Follow-Up:

Three follow-up sessions are planned, equivalent to 30 hours of participants' time. These are required for the teacher participants.

- Research Study Communications

This function focuses on feedback from research drafts written at the end of the summer research institute with mentors providing advice on the revision process. It allows continued access to research facilities and offers technical presentation guidelines focusing on visual aids, such as posters.

- TTU Annual Research Day

The RET teachers participate in the annual TTU research day on campus. Pre-service teachers and representatives from manufacturing interests are invited to attend.

- Focus on Pedagogy (Legacy Module Conference)

This serves as the ending event for one year. Participants share their developed Legacy Cycle modules with one another and with conference attendees.

5. RET Additive Manufacturing Study

RET Study was conducted using a monochromatic/colored 3D printer made by ZCorp. The drawings were created using Pro/Engineer, SolidWORKS, and ZPrint software. The data was analyzed by looking at one object at a time in monochrome. Experimental data was gathered by printing the objects one per run in monochrome. The objects were analyzed at three places in the building tray, front, back and center. The objects were rotated or oriented at 0°, 30°, 45°, 60°, and 90°. The data was gathered for thicknesses of 0.0035 inches and 0.004 inches. The following are the conclusions of the analysis of the data.

5.1. Layer Thickness versus Time

The layer data was analyzed for two layer thicknesses; 0.0035 inches and 0.004 inches. The data shows that the thinner layer thickness, 0.0035 inches, yields a longer production time. This is a logical conclusion since a thinner layer thickness will mean the object will be constructed of more layers, thus taking longer to print.

Figure 1 illustrates layer thickness versus time for a simple object that has 38 layers at a layer thickness of 0.004 inches and 43 layers at a layer thickness of 0.0035 inches. The graph indicates that the object will take 6 minutes to produce with a layer thickness of 0.004 inches, but it takes 9 minutes with a layer thickness of 0.0035 inches.   This means that it will take 33.3% more time to print 11.6% more layers.

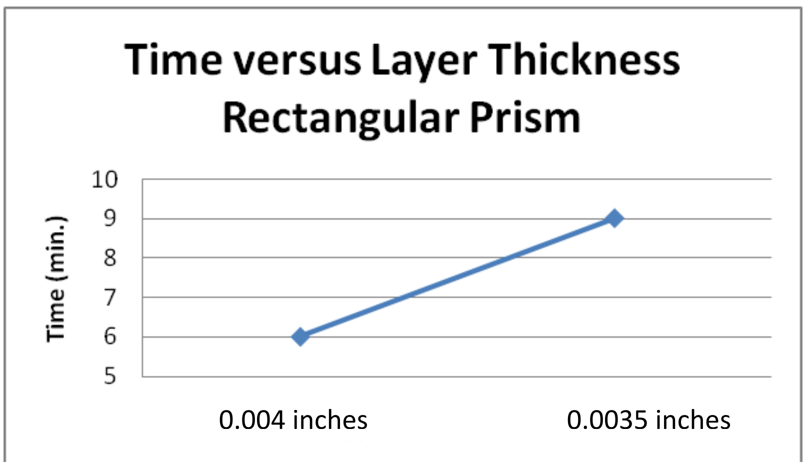


Figure 1: Time versus Layer Thickness Analysis: production of a rectangular size object

The example in *figure 2* illustrates a complicated object that takes 136 minutes to print with a layer thickness of 0.004 inches using 817 layers and takes 154 minutes to print with a layer thickness of 0.0035 inches using 933 layers. This example takes 11.7% more time to print 12.4% more layers.

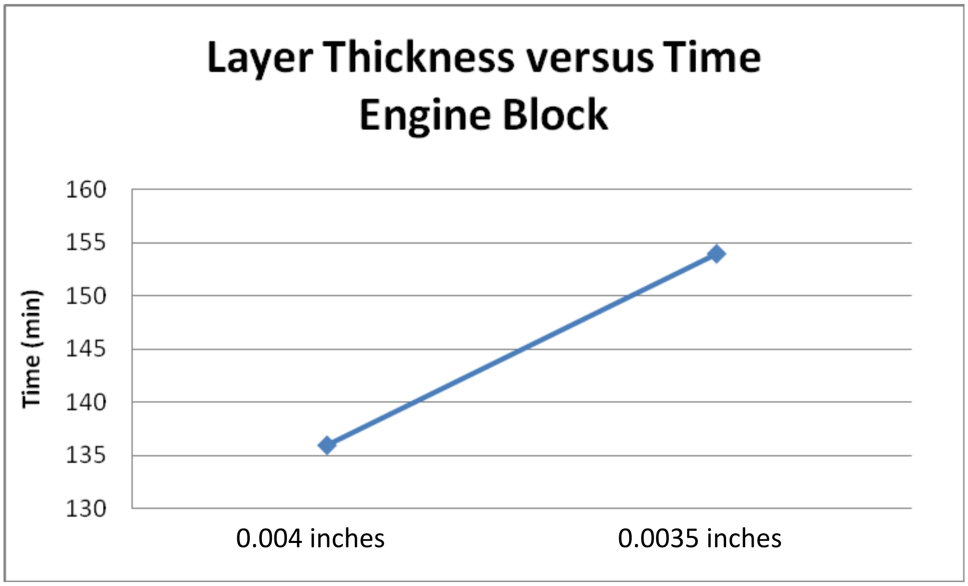


Figure 2: Time versus Layer Thickness Analysis: production of an engine block

The example in *figure 3* illustrates an object of medium complexity. It has 499 layers at 0.004 inches taking 100 minutes to print and 571 layers at 0.0035 inches taking 111 minutes to print. This represents a 12.6% increase in layers with a 9.9% increase in time.

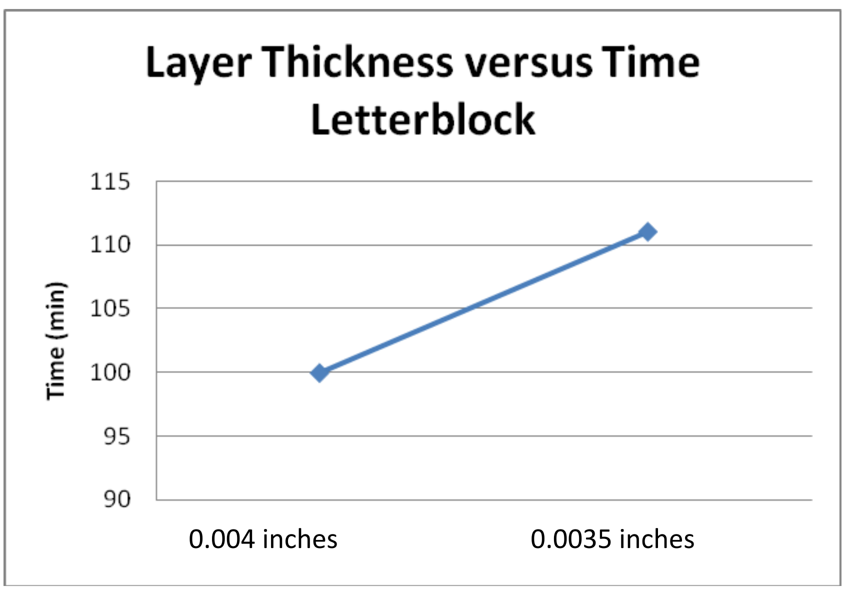


Figure 3: Time versus Layer Thickness Analysis: production of a letterblock

These results indicate no correlation between the complexity of the object and the layer thickness versus time, but there is a positive correlation between the decrease in layer thickness and the time required to print an object.

5.2. Location versus Time

Research was conducted with location versus time to identify how the time changes in relation to the location of the object in the production tray. The default placement in the ZPrint software is to the back left corner. After analyzing all the objects at all nine positions in the production tray (see *figure 4*), it was evident that all the left positions yielded the same times, all the right positions yielded the same times, and all the center positions yielded the same times. The time differences were in positioning the object in the front, back or center of the production tray.

left back	**center back**	**right back**
left center	**center center**	**right center**
left front	**center front**	**right front**

Figure 4: 9 Location Settings of the 3D Objects

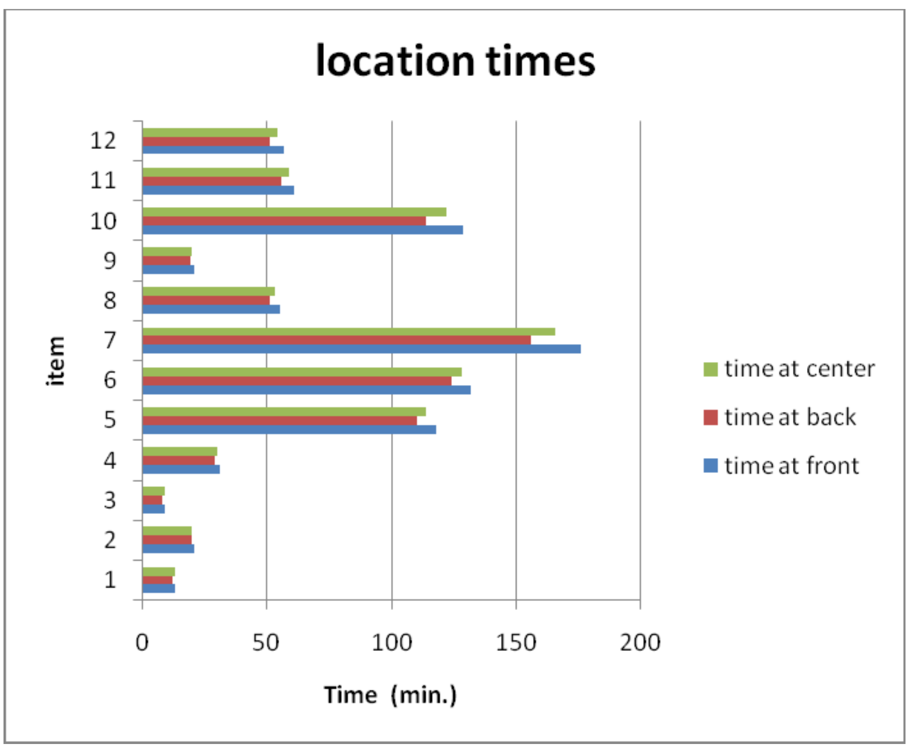


Figure 5: Location Times at the Front, Back, and Center of Production Tray

As evidenced in *figure 5* the back of the tray yields the fastest time. The front of the tray yields the slowest time. The time at the center of the tray is the mean of the front and back times.

The conclusion drawn from this analysis is that the software default, left back, is the fastest print time for any object regardless of size, complexity, or orientation. Although it makes no difference if the object is to the left, center or right in the tray, the time controlling factor is the front, back or center.

5.3. Scale versus Time

3D printing is a relatively inexpensive technology, but the labor can be an expensive factor. In this research we analyzed how scaling an object effects the time in production.

Figure 6 shows scaling data for three objects of varying complexities. It was found that the larger the original object, the more drastic was the time change when that object was scaled down by 50%. For these three objects scaling down 50% saved an average 64.4% more time over producing the object at 100%.

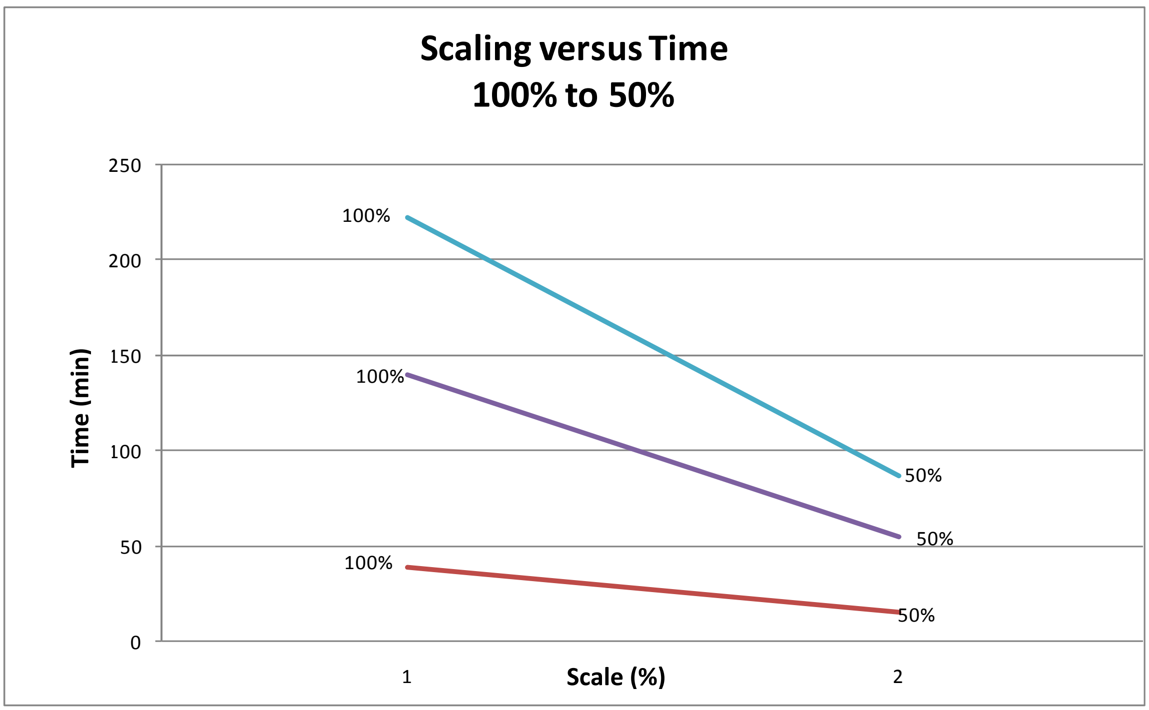


Figure 6: Scaling versus Time Analysis of Three Objects

Figure 7 illustrates the scale versus time for one object. You will notice that the change in time is an exponential relationship. As the object is scaled down, the time gets exponentially smaller.

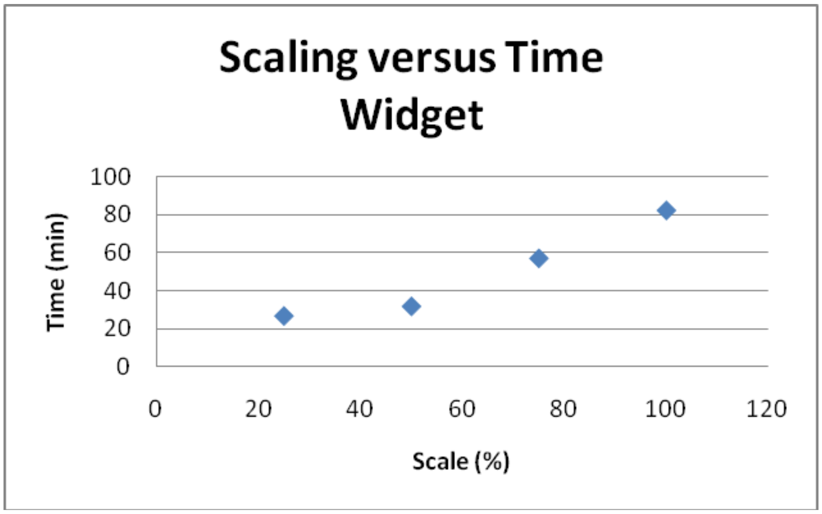


Figure 7: Scaling versus Time Analysis of A Widget

Since this technology is primarily used for the purpose of prototyping and for visual perspectives only, when exact size is irrelevant, scaling down will save time and money.

5.4. Orientation versus Time

This research also looked at the orientation of the object in the production tray relative to time. The objects were analyzed by rotating them 0°, 30°, 45°, 60°, and 90° around the xz plane. *Figure 8* shows an object oriented at 0° while *figure 9* shows the same object oriented at 30°.

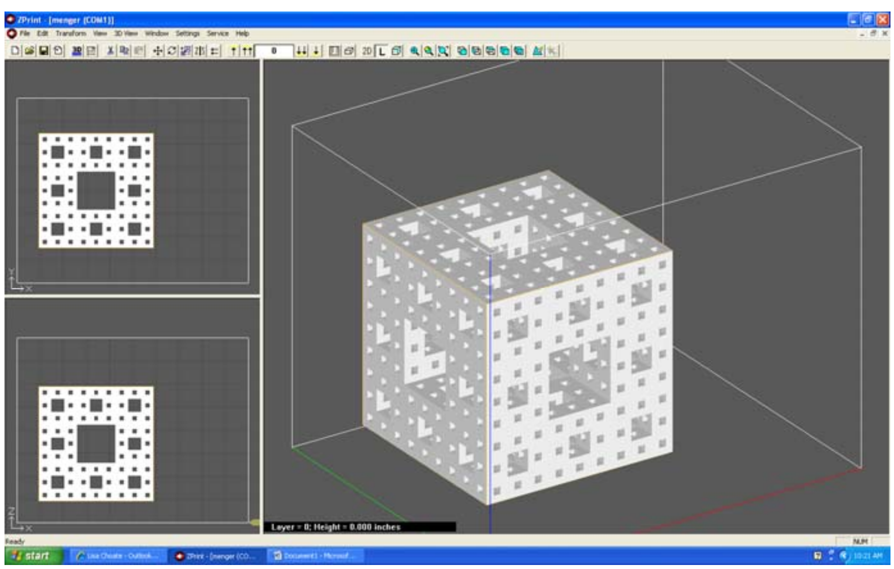


Figure 8: Test Object at 0 Degree Angle

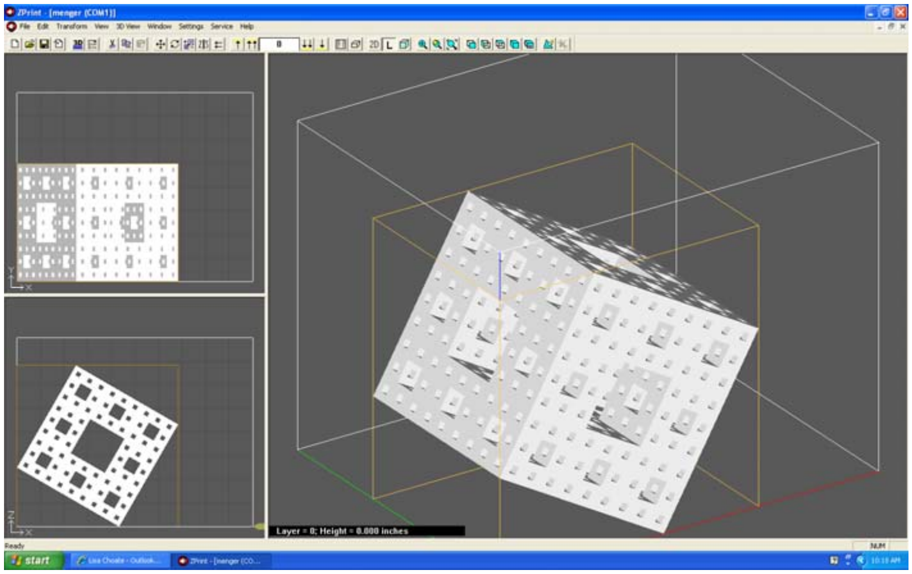


Figure 9: Test Object at 30 Degree Angle

When the orientation versus time data was analyzed no statistical correlation was found. It was discovered that the change in orientation versus time relationship fluctuated relative to the geometric variables of the object. Additionally, scale and position provided no correlation to orientation.

5.5. Estimated Time versus Experimental Time

Data was gathered for the estimated production time for an object, then the object was printed and the experimental time was recorded. For ten objects of varying complexity, scale, orientation and location the mean error was -1.001 minutes (see *figure 10*). The estimated time was under the experimental time by 1 minute.

estimated time	experimental time	error
15	14.033	0.9667
15	16.633	-1.63
31	32.733	-1.73
84	80.666	3.33
50	53.317	-3.317
22	21.5	0.5
31	33	-2
49	50.43	-1.43
40	43.7	-3.7
	average error	**-1.001**

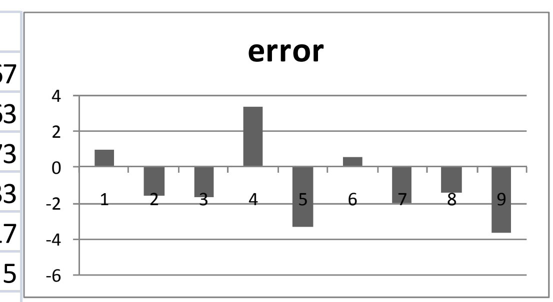


Figure 10: Estimated versus Real Production Times

As the objects were being printed it was noted that the machine took about 45 seconds from the start up to the time it actually started printing. When the experimental time was reduced by 45 seconds, the estimated time was closer to the experimental time (see *figure 11)* the mean error was reduced to -0.491 minutes. This shows that the estimated time was only under the experimental time by a little more than 29 seconds.

After analyzing the estimated time versus experimental time data it was concluded that the estimated time is reliable.

estimated time	experimental time - 45 sec	error
15	13.2833	1.48
15	15.883	-0.83
31	31.983	-0.983
84	79.9166	4.08
50	52.567	-2.567
22	20.75	1.25
31	32.25	-1.25
49	49.68	-0.68
40	42.95	-2.95
	average error	-0.491

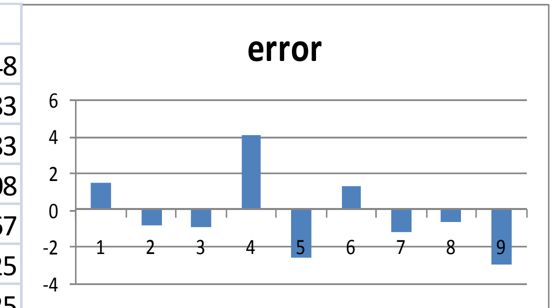


Figure 11: Production Time research with 45 seconds delay

5.6. Estimated Binder Usage versus Experimental Binder Usage

The 3D printing process involves two materials, powder and binder. The binder is expensive at about $425 per gallon (or 3,785.41178 ml).The estimated binder usage data was gathered, then nine objects were printed and the binder usage was recorded.

The research revealed that the binder usage was overestimated with a mean error of 21.04 ml (see *figure 12).*

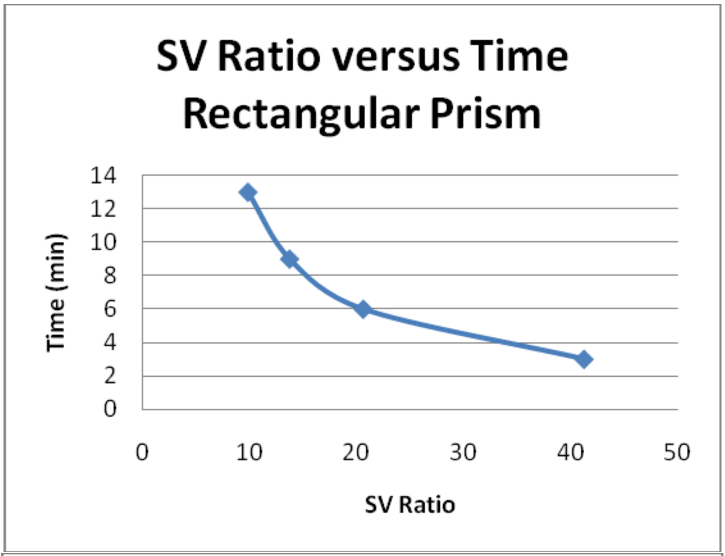
binder usage estimate (ml)	binder usage experimental (ml)	Error
34.4	27.3	7.1
34.4	29.3	5.1
66.3	47.3	19
104	69	35
116.3	104.7	11.6
52.6	34.3	18.3
70.8	47	23.8
104.2	66.5	37.7
90.3	58.5	31.8
	mean error	21.04

Figure 12: Differences between the Estimated and Real Binder Usage

5.7. Surface Area to Volume Ratio versus Time

The surface area to volume ratio (SV ratio) is found by dividing the surface area of the object by its volume. Each object in our research was scaled to 100%, 75%, 50% and 25%. The SV ratio for each scale was analyzed. It was found that as an object was scaled down, the surface area decreased slower than the volume. This phenomenon caused the SV ratio to increase quickly.

As illustrated in *figure 13* as the SV ratio increases the time decreases. This is an exponential relationship.



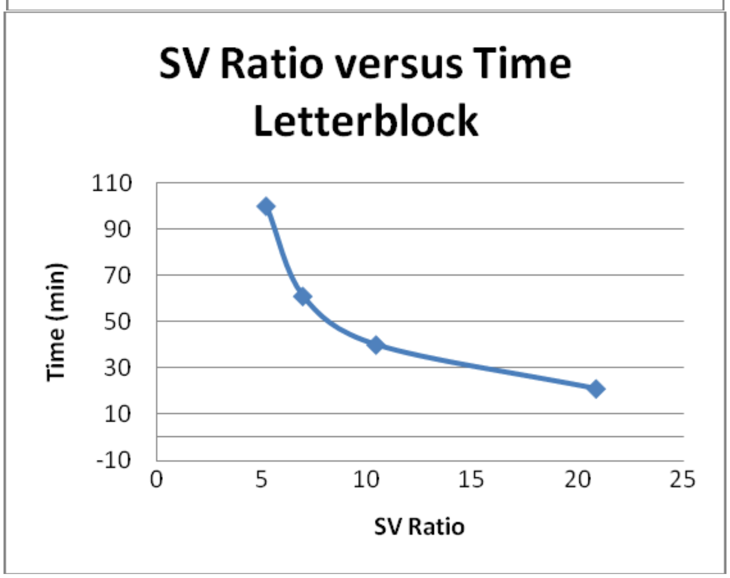


Figure 13: Relationship between SV Ratio and Production Time

5.8. Weights

In this research we studied the weights of 30 printed hands. All the hands were printed in the same position in the production tray using the same scale and orientation. Although all the hands were identically processed, their weights were different with no two hands having the same weight. The scale used to weight the objects had a precision of 0.0001 grams. After weighing all 30 hands, we infiltrated them with commercial hardener then reweighed them. The mean weight before infiltration was 41.5285 grams with a standard deviation of 0.6749 grams. The mean weight after infiltration was 45.5789 grams with a standard deviation of 0.6274 grams. Infiltration made the hands heavier and brought them closer to the same weight as evidenced by the smaller standard deviation. This is deviation is less that 1.5% of the mean weight.

The difference in the weights is the result of the process used to bind the material together. The powder is made of small particles. These particles are bound together with an adhesive binder. Since all objects will have their powder particles bound together in different configurations, the air gaps will vary causing the difference in weights.

6. Beta Testing of the RET Project in Additive Manufacturing

The results of the analytical and experimental studies were tabulated and reported for the future uses of the findings. In the Fall 2010 semester, engineering students in two upper level manufacturing technology courses used the laboratory. Students completed designs and produced prototypes of various objects using the capabilities of the laboratory. Most of the experimental RET findings were double-checked and proven throughout students' hands-on practices.

7. Conclusions

3D printing technology is the future of conventional prototyping technologies. It is a relatively fast and inexpensive method of producing the mind's creations. Using the ZCorp Z406 machine, it was found that the ZPrint software reliably estimated the time needed to create an object. It was found that an object placed at the back of the production tray using a layer thickness of 0.004 inches was the fastest method of production. Scaling down an object decreases the time exponentially, and the orientation or rotation of the object versus the time it takes to print revealed no correlation. The relationship of orientation of an object versus time depends on the geometric characteristics of the object. It was found that as the surface area to volume ratio increases the time decreases and is an exponential relationship. It was also noted that the weights of objects created exactly the same were different, with a standard deviation of 0.6749 grams. The current results on these RET research study were used, re-tested and benchmarked in some manufacturing technology courses in Fall 2010.

8. Acknowledgements

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