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Improvements in operational readiness by distributing manufacturing capability in the supply chain through additive manufacturing

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THESIS

IMPROVEMENTS IN OPERATIONAL READINESS BY DISTRIBUTING MANUFACTURING CAPABILITY IN THE SUPPLY CHAIN THROUGH ADDITIVE MANUFACTURING

by

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December 2017

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This report assesses the effects that additive manufacturing has on unit operational readiness (OR) rates when used as part of a distributed manufacturing system. It provides an overview of the relevant Army supply and maintenance policies that affect the OR rate along with centralized and distributed manufacturing concepts. Additionally, the report compares and contrasts traditional and advanced manufacturing methods with additive manufacturing. This work decomposes the additive manufacturing processes into 11 primary functions. The time requirements for five of these functions are experimentally evaluated, providing the portion of time that each function contributes to the total additive manufacturing process. The results indicate that the printing time constitutes more than 95 percent of the total additive manufacturing time, suggesting that estimated print time is an acceptable surrogate for total manufacturing time.

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This report assesses the effects that additive manufacturing has on unit operational readiness (OR) rates when used as part of a distributed manufacturing system. It provides an overview of the relevant Army supply and maintenance policies that affect the OR rate along with centralized and distributed manufacturing concepts. Additionally, the report compares and contrasts traditional and advanced manufacturing methods with additive manufacturing. This work decomposes the additive manufacturing processes into 11 primary functions. The time requirements for five of these functions are experimentally evaluated, providing the portion of time that each function contributes to the total additive manufacturing process. The results indicate that the printing time constitutes more than 95 percent of the total additive manufacturing time, suggesting that estimated print time is an acceptable surrogate for total manufacturing time.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

3D	three-dimensional
ADT	administrative delay time
AM	additive manufacturing
AM CoP	additive manufacturing community of practice
A_O	operational availability
ASL	authorized stockage list
BJ	binder jetting
CAD	computer aided design
CCP	container consolidation point
CONUS	continental United States
CNC	computer numerical control
CWT	customer wait time
DA	Department of the Army
DLA	Defense Logistical Agency
DLP	digital light processing
DOE	Department of Energy
EBM	electron beam melting
EOD	explosive ordnance disposal
ERA	essential research area
Ex Lab	Expeditionary Laboratory
FDM	fused deposition modeling
FMC	fully mission capable
ICP	inventory control point
ILAP	Integrated Logistics Analysis Program
IR	infrared
LDT	logistical delay time
LOM	laminated object manufacturing
LRT	logistic response time
$\bar{M}$	mean maintenance time
MDT	mean maintenance down time
MRAP	mine resistant ambush protective
MRE	meal ready to eat
MJ	material jetting

MTBM	mean time between maintenance
NOD	night observation device
NMC	non-mission capable
OCONUS	outside the continental United States
OR	operational readiness
PLA	polylactic acid
POD	point of debarkation
POE	point of embarkation
RAMBO	rabidly additively manufactured ballistics ordnance
REF	Rapid Equipping Force
RWT	requisition wait time
SLA	stereolithography
SLM	selective laser melting
SLS	selective laser sintering
SSA	supply support activity
TAMMS	The Army Maintenance Management System
TDD	time – definite delivery
VTC	video teleconference

EXECUTIVE SUMMARY

According to the Army's 2010 version of the Unit Status Reporting and Force Registration Regulation 220-1, units must maintain a 90 percent operational readiness (OR) rate. This goal can be challenging even when units have access to their complete authorized stockage list (ASL) and are located near their supporting supply support activity (SSA). Meeting the OR rate is often tougher for deployed units operating with a reduced ASL while geographically separated from the SSA. This report investigates the possibility of incorporating a distributed manufacturing concept into the current supply system to improve unit OR rates. Furthermore, it experimentally evaluates the impact that pre and post processing activities have on the total time required to produce additively manufactured parts.

With the assistance of the 2003 edition of the Department of Defense Supply Chain Materiel Management Regulation, several locations inside and outside the continental United States supply chains were identified as possible locations to incorporate distributed manufacturing. Incorporating existing additive manufacturing facilities, specifically Army research laboratories, into the supply system proved not to be effective to reduce OR rates. The primary drawback to this option was the requirement that parts manufactured at research laboratories need to travel through the whole supply chain; therefore, mean maintenance down time (MDT) is increased by the manufacturing days and thus decreases the OR rate.

The next location investigated was at the inventory control point that is only two days into the supply chain. This location also suffers from its early position in the supply chain. One benefit of the early position in the supply chain is the ability for a facility to serve a larger population. However, if the additive manufacturing time for a part at this location exceeds two days, then the OR rate will suffer in comparison to existing processes. Similar to locating distributed manufacturing capabilities at the inventory control point is to locate the manufacturing capability at the container consolidation point. These locations have the same early process issue; the container collection point is only one day further in the supply chain.

The port of debarkation is the first truly viable location for distributed manufacturing capabilities to improve OR rate. This location is approximately 10 days along the supply chain, only one day from the customer. This location could have a significant improvement on unit OR rates. The only location that would have more impact is to have manufacturing capabilities at the supporting unit SSA or better yet at the unit. The major drawback with these locations is the relatively restricted population they can serve.

A unique aspect of incorporating manufacturing capabilities in the supply chain is that it provides stakeholders more decision space for evaluating the importance of OR rate versus supply time. This research revealed that by changing the MDT for a repair part, one could sacrifice part reliability without impacting OR rate. The result is whatever portion of the MDT changes, the same proportion of part reliability can be accommodated without affecting availability. Therefore, if a part can be received in half the time, the reliability of that part need be only half as good to maintain the same OR rate.

The final evaluation in this report is the amount of time required to perform the step of the additive manufacturing process. A flow block diagram was used to identify the 11 steps of the additive manufacturing process. The demonstration covered five of these steps revealing that printing the part consumed 96 percent of the total manufacturing time. The remaining time was used to prepare the printer and post process the final part. The part configuration and material used appeared to have little influence on the print time. The primary factor affecting print time appears to be the printer. The test also demonstrated that printing multiple parts on a single build plate has no discernable impact on individual manufacturing time.

Other than hypothesizing possible locations within the supply chain to locate distributed manufacturing capabilities this report also revealed three primary results. First, MDT can be used to estimate required part reliability necessary to mitigate negatively impacting OR rates. Second, printing comprises 96 percent of the total additive manufacturing time, with little difference based on part type or printer type. Finally, there is no time advantage of printing multiple parts on a single build plate.

Although the Army currently has distributed manufacture capabilities such as expeditionary laboratories, the Army should invest in 3D printing capabilities as close to the unit level as possible to have the greatest potential to improve OR rates. Furthermore, given that the print time comprises 96 percent of the total additive manufacturing time, investment should focus on printer quality, rather than on training to reduce processing time. By providing even basic polymer printers to units, overall OR rates have the potential to improve.

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I. INTRODUCTION

A. BACKGROUND

Distributed manufacturing is a type of manufacturing network that allows organizations to produce multiple goods at various locations. The improvement of advanced manufacturing technologies such as additive manufacturing, laser cutters, and computer numerical control (CNC) machines have made distributed manufacturing available to organizations of all sizes. In March 2017, the acting director of the U.S. Army Research Laboratory, Dr. Philip Perconti, listed “science for manufacturing at the point of need” as an essential research area (ERA) (McNally 2017, 1). This concept of distributing manufacturing capabilities to the location where repair parts are needed could have a significant impact on the current supply and maintenance concepts that support deployed soldiers in terms of operational readiness (OR).

B. PURPOSE OF RESEARCH

The Army’s maintenance goal is to maintain an OR rate of 90 percent for each type of combat system (Department of the Army [DA] 2010, 51). This goal can be challenging for units to maintain when they possess a full authorized stockage list (ASL) and are close to their supporting supply support activity (SSA), as when in a garrison environment. Meeting the OR rate while deployed becomes tougher since the units may be geographically separated from the supporting SSA and operating with a reduced ASL. Investigating potential strategies for improving OR rates is a major motivation for this research.

Outside of the Army, OR rate can be thought of as operational availability (A_O), which is an indirect measure of system maintainability. Even though these terms are sometimes used synonymously, as they are calculated similarly, there is a slight difference. The difference is due to how *The Army Maintenance Management System (TAMMS) User Manual* (DA PAM 750-8) mandates specific types of failures to be reported. For the purpose of this report, these terms will be used interchangeably unless explicitly stated otherwise.

According to Blanchard and Fabrycky's 2011 edition of *Systems Engineering and Analysis*, A_O is determined by the ratio of mean time between maintenance (MTBM) and the sum of MTBM and mean maintenance downtime (MDT). For the A_O ratio, MTBM is a measure of reliability and MDT is a measurement of maintenance and supply times. Therefore, to improve a system's $A_{O,}$ either component reliability on a system has to increase and/or supply and maintenance time must decrease. This research assumes that distributed manufacturing techniques will have no direct effect on maintenance time. That is, the repair time for a faulty part is not impacted by the origin of the replacement. Accordingly, this research focuses on alternative methods of improving operational availability.

Recall that the general motivation of this research is an investigation of the factors that impact OR rates. More specifically, this research demonstrates the effects that distributed manufacturing may have on the current Army supply concept. First, the research investigates the current supply performance by evaluating customer wait times within the continental United States (CONUS) and outside the continental United States (OCONUS). These times are compared to supply time goals outlined in Department of Defense Supply Chain Materiel Management regulation (DOD 4140.1-R). Second, the report presents the results of laboratory tests designed to evaluate additive manufacturing time of four repair parts.

C. RESEARCH OBJECTIVES

This report addresses the following objectives while investigating the effects that distributed manufacturing has on the current Army supply concept.

1. Primary Objective

- Identify the critical functionality associated with additive manufacturing and demonstrate the time proportionality of each step of the additive manufacturing process.

2. Subsidiary Objective

- Identify considerations that affect the incorporation of distributed manufacturing within the current Army supply system.
- Assess the results of the additive manufacturing time requirements.
- Based on the experimental results, recommend the point in the supply process where additive manufacturing has the largest potential impact on operational readiness.

D. BENEFITS OF RESEARCH

Operational availability calculation is based on two primary variables, MTBM and MDT (Blanchard and Fabrycky 2011, 427). Mean time between maintenance is a cumulative reliability result of the system's components. The MTBM is determined by the system design and system use. Generally, inferior design and/or inferior parts will degrade system reliability and decrease MTBM.

This research focuses on the MDT which Blanchard and Fabrycky (2011) calculate using three components: administrative down time (ADT), mean maintenance time ($\overline{M}$), and logistical delay time (LDT). Administrative delay time is assumed not to be affected by manufacturing location, as the repair part still needs to be requested and received. $\overline{M}$ may be affected by advanced manufacturing techniques by making it possible to create assemblies as one component. However, changes in part design are beyond the scope of this report.

The longest delay in repairing a system is often LDT. The military has tried to improve the logistical system by adopting civilian supply chain management techniques and new technologies. The government accountability office high risk reports since the early 1990s revealed that these methods have improved inventory control and in-transit tracking of repair parts. Predictive maintenance and supply models also have improved units' ASL. However, due to available cargo space, units are limited to the quantity of repair parts they are able to carry and deploy.

This research investigates the effect that manufacturing location has on LDT and thus, system maintainability. Additive manufacturing is just one of many manufacturing processes available to the Army to produce repair parts at the point of need to reduce LDT. The intent of this research is to provide insight into how advancements in manufacturing may affect current understanding of supply chain management, which may improve overall system operational availability and unit readiness.

E. LIMITATIONS OF RESEARCH

Manufacturing techniques used within a distributed manufacturing concept vary depending on organizational need. The use of computerized manufacturing equipment has made advanced manufacturing the primary method for distributed manufacturing. The range of advanced manufacturing methods is too extensive to cover in this report. This report focuses on the use of additive manufacturing technique, specifically fused deposition modeling (FDM) 3D printing. This is chosen due to availability for experimentation and prevalence within the military. According to the Navy's additive manufacturing page on milsuite.mil, a military professional working group web site, as of October 5, 2016, FDM printers accounted for over half of the printers owned by the Navy (Nuss 2014).

Supply times vary depending on supply method and location. As a way to simplify the Army supply times, customer wait time will be evaluated by geographic supply area and not per unit. Due to restrictions placed on the Army's supply management systems, current supply data is unavailable for this report. Therefore, this report uses published historical data.

F. METHODOLOGY

This research assesses the manufacturing time of 3D printed parts. Manufacturing times for 3D printed parts are found experimentally using four parts built with two different FDM printers in four different materials. The experimental manufacturing time includes printer set up, printing and post-processing times. Furthermore, this research evaluates the Army supply system based on military regulations and published reports and makes recommendations regarding the integration of AM into this process based on experimental results.

G. ORGANIZATION OF REPORT

The remainder of this report is divided into four chapters. Chapter II is a literature review of the Army supply and maintenance system, manufacturing methods and the Army's use of different manufacturing methods. Chapter III evaluates the Army supply system, comparing regulatory supply times to historical supply data and provides maintainability calculations. Chapter IV reports the results of distributed manufacturing time. The final chapter summarizes the findings within this report, makes recommendations based on those findings and recommends further areas of research.

H. SUMMARY

This chapter provided a general overview of distributed manufacturing along with the Army's desire to investigate the use of distributed manufacturing at the locations where repair parts are required. The chapter continued with the purpose and methodology of the research and explained the limitations, experiments and data collection. Finally, this chapter provided an overview of the arrangement of the report.

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II. CONTEXTUAL REVIEW

A. INTRODUCTION

To assess whether additive manufacturing used as part of a distributed manufacturing system can impact maintainability of Army systems, one must first have a basic understanding of Army logistics and plausible distributed manufacturing methods. This chapter provides a literature review the Army supply and maintenance system. It provides a foundation for manufacturing techniques, methods, and concepts, specifically additive and distributed manufacturing. Finally, this chapter examines how the Army is currently using additive and distributed manufacturing.

B. ARMY SUPPLY SYSTEM

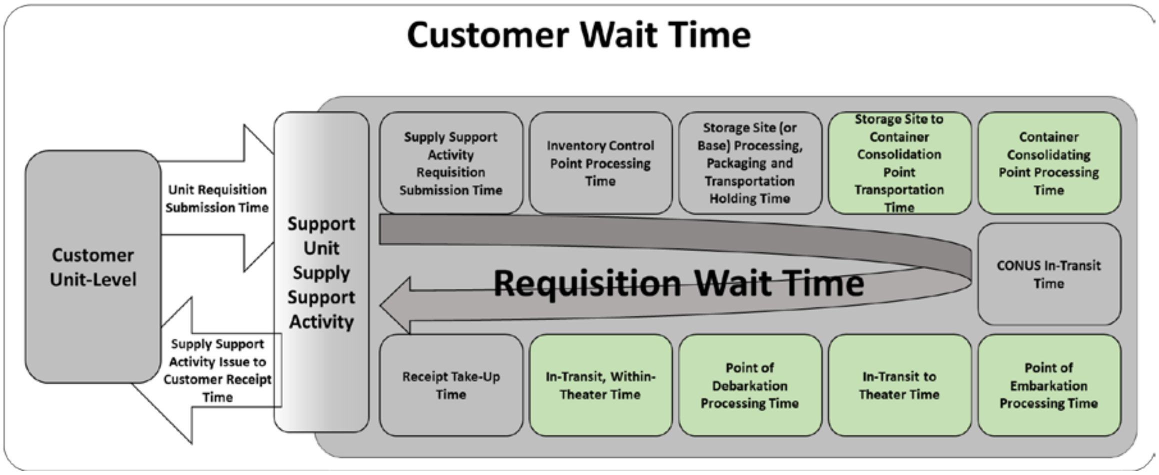
The Army's supply system begins and terminates at the unit. The unit maintains a limited number of repair parts as part of their ASL. Regulations limit quantity of repair parts to frequently used repair parts. A unit's ASL is further limited by the volume of spare parts that it is able to transport while deployed. If repair parts are not available in the unit's ASL, the unit supply or maintenance clerks initiate the supply process by ordering repair parts through the Army maintenance management system (TAMMS). The supporting supply support activity (SSA) receives the request from the unit. If the supporting SSA is unable to fill the request, the request is forwarded to other SSA on that base before being forwarded to national warehouses operated by the Defense Logistics Agency (DLA) if required. If DLA is unable to fill the request from one of its national warehouses, a vendor will receive the request.

The lowest level support organization that can fulfill the order ships the part to the next level of support until the unit receives the repair part. The exceptions to this supply fulfillment process are when the vendor or DLA is capable of shipping directly to the unit using commercial transportation companies. The process is similar for both continental United States (CONUS) and overseas (OCONUS) locations. However, the transportation process for deliveries OCONUS involve more steps designed to improve shipping efficiencies.

The additional OCONUS steps include consolidating supplies at the CCP designed to reduce shipping inefficiencies of a more complex system. Additional time may also be due to the longer distances traveled. The fulfillment time for a requisition to navigate this process either CONUS or OCONUS is generally called logistic response time (LRT) (ACQuipedia 2016).

The SSA uses the requisition wait time (RWT) as their LRT metric to determine the efficiency of the supply system (RAND 2003, 1–2). This metric specifies the time required for a part ordered by an SSA to be received by that SSA (RAND 2003, 2). Requisition wait time is a subset of LRT experienced by the unit.

Customer wait time (CWT) is the LRT metric from the customer perspective (RAND 2003, 1). Although CWT is similar to RWT, CWT includes the requisition time from the unit to the SSA, and issue time from when the SSA issues the part to the time the unit clerk accepts the issued item in the unit's supply control system, which is not included in RWT (RAND 2003, 1–6). This relationship between RWT and CWT is depicted in Figure 1. Due to the additional steps prior to and after the RWT, CWT better captures equipment down time due to logistical delays. Therefore, CWT is often the metric used when estimating operational availability. Although these metrics can be used for all classes of supply, this work will focus only on class IX, which are repair parts.



CWT includes all the RWT. The steps highlighted in green depict the additional steps required for OCONUS supply processing. Adapted from Department of Defense (2003); RAND (2003).

Figure 1. Relationship between RWT and CWT.

C. CURRENT ARMY MAINTENANCE PROCESS

The Army focuses on two aspects of unit readiness, personnel and equipment. Personnel readiness consists of personnel force level and training. Equipment readiness focuses on availability only—does the unit have the correct equipment and is that equipment in working condition?

Depending on equipment type, the Army calculates availability based on time-based rates. Often, the Army tracks critical equipment, such as airframes and combat systems like Abrams main battle tanks or Bradley fighting vehicles, on an hourly scale. The granularity of hourly tracking of critical equipment down time highlights the importance of having spare parts on hand to meet the Army desired 90 percent OR rate (DA 2010). Meeting the OR rate is only a matter of maintenance competence if the repair part is available in the unit’s ASL. The degree of difficulty in maintaining the unit’s OR rate increases whenever the repair part is requested from the supply chain. If the repair part is back-ordered at the manufacturer, meeting the OR rate may be infeasible.

The Army currently has two processes in place that may be leveraged to assist commanders in managing the operational availability of their equipment. The first method is command substitution. This process allows the unit commander to switch parts between systems to keep as many systems fully mission capable (FMC) as possible. According to Army Regulation 750-1, the commander can authorize the use of parts for one piece of equipment to be used on another piece of equipment, increasing the A_O for the latter and decreasing the A_O for the former (DA 2007, 41). Exchanging parts allows for one piece of equipment to be non-mission capable (NMC) for multiple faults instead of multiple pieces of equipment being NMC for a single fault each. Therefore, if a unit has a fleet of ten fuelers and two are NMC the unit's OR rate for fuelers is 80 percent. But if functioning parts from one NMC fueler are able to replace the faulty parts of the other NMC fueler, the unit's OR rate for fueler will increase to 90 percent.

Although the method of command substitution described above is effective to manage the OR rate, it often leads to one piece of equipment becoming a donor for that family of equipment within a command. If improperly managed, this donor is at risk of reaching a state where is it is not fiscally reasonable to repair. This program may also draw upon equipment that is in the Defense Reutilization and Marketing Office (DRMO) program. DRMO is a program where excess or damaged equipment is sold, scrapped or recycled.

Circled X is the second process. The term "circled X" refers to the commander circling the fault symbol, X, on Department of the Army (DA) Form 2404, the equipment maintenance log. The circled X identifies the system has a fault, but the commander authorizes the system for use. DA Form 2404 states that a circled X "indicates a deficiency, however, the equipment may be operated under specific limitations as directed by higher authority or as prescribed locally, until corrective actions can be accomplished" (DA 2011). Circled X status is a temporary status that is valid only for a single mission or day, whichever is shortest (DA 2005, 43–44). Circled X only affects the operation of the equipment and not the reported status (DA 2005, 44).

This process simply states that the commander understands there is a specific fault and the commander assumes responsibility for the operation of that equipment with the given fault. Often the commander will include restrictions on the use of that piece of equipment directly on the DA Form 2404. For example, if a truck has faulty headlights, the commander may authorize the use of the truck with a circled X with a restriction to operate the truck only during daylight hours.

Since the circled X process does not remove the fault from reporting requirements, circled X faults remain a valid fault that a permanent repair part can be requisitioned against while a 3D printed part is temporarily being used to meet mission requirements. This scenario, where the equipment is allowed to be operated under the circled X process but is still being reported as NMC, is the only known instance when the OR rate and A_O are not the same. In this situation, the equipment with a circled X fault must be counted as NMC which reduces the OR rate. However, since the equipment can be used, the A_O improves.

Both command substitution and circled X processes are examples of the Army's willingness to accept less than optimal performance from individual parts if that decrease in performance can increase the overall system availabilty. Along those lines, additive manufactuing is another technique for making parts available, some cognizant of manufacturing in consistency, to individual units with the goal of improving availability. Currently, all branches of the military are producing non-critical parts, such as nobs and dust covers, using additive manufacturing (AM). Their concerns are using AM processes to manufacture critical repair parts since the production repeatability and reliability of the parts are not well understood (Merritt 2015, 9). The Army's Additive Manufacturing Community of Practice (AM-CoP) is attempting to leverage the circled X processes to allow the use of AM repair parts on all Army equipment. The AM-CoP intention of using the circled X process allows the commanders to operate in a trade-space between using repair parts with unknown reliability or have a known limitation to a piece of equipment.

D. MANUFACTURING TYPES

Manufacturing consists of manufacturing networks, modes, and techniques. Manufacturing networks describe the organization of manufacturing facilities. Centralized manufacturing describes an organization's manufacturing network that has a single factory that produces all of their products. This definition is expanded to include a network of manufacturing facilities where each facility produces their own unique products. Decentralized or distributed manufacturing is when an organization uses multiple facilities to manufacture goods. This definition is limited to manufacturing networks that have interchangeable manufacturing facilities that are capable of producing multiple products.

Within each manufacturing network are two groups of manufacturing methods – traditional manufacturing and advanced manufacturing. Traditional manufacturing is often prominent in centralized manufacturing due to equipment size, and the uniqueness of tooling. Traditional manufacturing typically consisting of non-computer based manufacturing techniques such as forging, milling, casting, molding, and stamping where one machine is used to make a large quantity of a limited type of distinct parts. Conversely, advanced manufacturing consists mainly of computer aided manufacturing techniques such as additive manufacturing (AM), Computer Numerical Control (CNC) milling and laser cutting where one machine is capable of producing a range of products with few or no tooling changes.

Due to the flexibility of advanced manufacturing methods, this manufacturing concept is finding its way into centralized production networks; primarily to produce rapid, cost effective traditional manufacturing toolings such as dies, stamps, and casts. With the progress of all advanced manufacturing techniques, these methods are being used as a cost-effective alternative to traditional manufacturing processes. The same benefits that are bringing advanced manufacturing into centralized manufacturing networks are allowing traditional manufacturing methods to appear in distributed manufacturing networks.

Additive manufacturing (AM) is the primary advanced manufacturing technique that is making it affordable to use traditional manufacturing processes and machines in distributed manufacturing facilities. There are nine primary AM methods commonly referred to as three-dimensional (3D) printing. Table 1 summarizes the most common types. This table lists of the most common printing materials and provides a brief description of how the printer functions. Finally, Table 1 highlights advantages and disadvantages of each printer type.

Table 1. Additive Manufacturing Types. Adapted from Locker (2017); Sculpteo (2017)

Additive Manufacturing Types	**Material**	**Description**	**Advantages**	**Disadvantages**
FDM–Fused Deposition Modeling	Plastic	Prints using a filament extruded through heated nozzle	Cost effective printer used for fabricating small durable parts primarily for prototyping	Requires supporting structure
MJ–Material Jetting (Wax Casting)	Plastic or Wax	Printing process similar to FDM	Automates wax casting process	Printed parts are fragile
SLA–Stereolithography	Photopolymers	Uses UV light to cure a layer of photopolymer	Creates extremely detailed surfaces	Requires support structures; Post processing may include solvent wash and UV baking
DLP–Digital Light Processing	Photopolymers	Similar to SLA but uses a projector to cure an entire layer of resin at once	Faster than SLA with similar surface details	Requires support structures; Post processing may include solvent wash and UV baking
SLS–Selective Laser Sintering	Plastic, Glass, Ceramics, Metal	Similar to SLA but uses a laser to sinter powder rather than a UV light to cure resin	Able to print in a larger range of materials	Requires high power lasers, and special post processing equipment, making this type of printer expensive
SLM–Selective Laser Melting	Metal	Similar to SLS but melts the powder printing material	Able to print in metal	Requires high power lasers, and special post processing equipment, making this type of printer expensive
EBM–Electron Beam Melting	Metal	Similar to SLM but uses an electron beam to melt metallic powder printing material	Able to print in stronger metals	Expensive process that requires a vacuumed build chamber and special post processing equipment
LOM–Laminated Object Manufacturing	Paper, Plastic, Metal	Prints by layering precisely cut sheets of material	Fast print time and most affordable 3D printing methods for printing large parts	Less dimensionally accurate than SLA or SLS
BJ–Binder Jetting (Powder bed Printing)	Plastic, Ceramic Metal, Sand	Used a binder to hold powder substrate together	Able to print a single part in full color. Able to print with metallic binders making it possible to print circuits	Generally lacks structural integrity

E. THE ARMY'S USE OF ADDITIVE MANUFACTURING

Traditionally, the primary use of additive manufacturing (AM) was rapid prototyping. The Army continues to use AM in the prototyping role while researching the usefulness and practicality of AM in the production and maintenance of materiel. The Government Accountability Office (GAO) report GAO-16-56 highlights some of the advancements of AM within the military while considering the benefits and challenges of using this technology in the military.

The GAO report outlines the benefits already realized by the military's use of AM including

> reduced time to design and produce functional parts; the ability to produce complex parts that cannot be made with conventional [traditional] manufacturing processes; the ability to use alternative material with better performance characteristics; and the ability to create highly customized, low-volume parts. (Merritt 2015, 9)

The report describes a key challenge of AM, which is ensuring the quality of functional parts, specifically the repeatability of part quality and manufacturing tolerances (Merritt 2015, 9). Thus, a 3D printed part may possess better performance characteristics, but the manufacturing repeatability and part reliability may suffer.

The GAO report echoes the industry philosophy. Carbon 3D printer's slogan of "Stop Prototyping, Start Producing" (Carbon n.d.) clearly states where the AM industry is heading, away from prototyping and toward large-scale production. The Army, in conjunction with the Defense Logistics Agency, determined that nuts and bolts were high demand items often out of stock in the Afghanistan theater of operation (Merritt 2015, 13–14). The Army began investigating the use of AM technologies to produce these high-volume items. As of August 2015, the U.S. Army Research, Development, and Engineering Command (RDECOM) Armament Research, Development and Engineering Center had produced several nuts and bolts demonstrating that AM parts could be used in equipment (Merritt 2015, 14). During this time, the Army planned additional qualification and functional testing, to which the results are unavailable for this report. (Merritt 2015, 14).

In early 2017, the Army made headlines when it debuted RAMBO (Rapidly Additively Manufactured Ballistic Ordnance), a 3D-printed grenade launcher. The 3D-printed weapon, modeled after the M203 grenade launcher, consists entirely of AM parts minus springs and fasteners (Mizokami 2017). The RAMBO project is a proof of concept system that investigated the possibility of using AM to rapidly prototype and produce armaments. As part of the project, grenades based on the M781 grenade design were built with AM and fired from the 3D-printed launcher (Batareyki.net 2017).

During the manufacturing of RAMBO the Army used several types of AM processes. As part of the post processing, “the barrel was tumbled in an abrasive rock bath and then Type III hard-coat anodized to provide a rugged finish” (Mizokami 2017) before assembling the launcher. The launcher’s barrel and receiver took approximately 70 hours to print and an additional five hours of post processing (Mizokami 2017). From this data point, post processing is approximately 6.67 percent of the total manufacturing time. It is unclear from the provided references if the post processing time includes assembling the weapon. It is presumed that it does not and the AM would not significantly affect the assembly time.

According to Batareyki.net’s video “R.A.M.B.O. – 3D-Printed Grenade Launcher” printing in zinc, the main material used in the construction of the M781 grenade, is not yet possible, forcing the army to use several techniques to print the rounds. The FDM process was used to print the windscreen and cartridge case. The Army used four AM methods to create the body of the projectile. One method used a softer aluminum alloy to print the grenade body. Another approach involved redesign of the grenade body with a groove that would accept a plastic operating ring. Then the Army printed the body in steel followed by using a rotation axis FDM printer to print the operating ring in the groove. The third method also used a steel printed body with a groove. However, with this method, a urethane ring was molded onto the body using an SLS printed injection mold. The final method used a wax printed body and the lost wax casting method to cast the body out of zinc.

The processes the Army utilized to create the RAMBO grenade highlights how multiple AM processes can be leveraged to accomplish the same goal. This shows that even though a given printer is unable to manufacture in a desired material there may be work-a-rounds that can be implemented to provide a part that performs the same function and is compatible with the larger system. Furthermore, the lost wax method used during this project is an example of combining advanced manufacturing technology with traditional manufacturing processes which may increase distributed manufacturing capabilities.

According the Mizokami's *Popular Mechanics* article, in October 2016, the Army conducted live fire testing of the RAMBO system. The test consisted of 15 shots, in which no degradation in the system was noticed. During this limited testing period the printed rounds reached a muzzle velocity within five percent of the standard M781 grenade. This test alludes that AM systems performs closely to traditional manufacture systems.

Other AM parts produced by the Army or used by the Army include

- The Tank-automotive and Armament Command (TACOM) contracted the production of 3D printed replacement cabs for three versions of the Low-Velocity Air Drop (LVAD) Medium Tactical Vehicle (MTV) (Syverson 2015, 57–59).
- Walter Reed National Military Medical Center produced cranial plate implants and medical tools (Merritt 2015, 23–24)
- ARDEC 3D printed a number of functional repair parts for iRobot's PackBot. Although the parts were printed as replacement parts, they have lightened the PackBot by six pounds (Clarke 2017).

In 2012, the Army Rapid Equipping Force (REF) delivered advanced manufacturing assets, including experienced designers and fabricators to soldiers in Afghanistan. Responsible for rapid implementation of material solutions, REF developed three mobile laboratories known as expeditionary laboratories or Ex Labs. With the aid of these labs, REF designed, prototyped and manufactured multiple items in a combat zone where the parts were required.

The Ex Labs are containerized facilities capable of provided manufacturing capabilities worldwide. A 20-foot shipping container contains the Ex Lab, consisting of advanced and traditional manufacturing capabilities. These capabilities include an FDM

3D printer, five axis Computer Numerical Control (CNC) lathe, and welder along with an assortment of other fabrication tools (Asclipiadis 2014). The lab also has a complete suite of electronic and diagnostic tools. According to the Ex Lab capabilities briefing provided by Michael Hudson (email to author, April 25, 2017), Ex Lab is operated by a staff of four, including two civilian engineers, one civilian technician, and one military member to act as a liaison between the production team and the military customers (M. Hudson, email to author, April 25, 2017).

A high-bandwidth satellite Internet link provides the lab virtual access to computing resources and instrumentation. The data link also provides the lab support and experience of CONUS REF team via video teleconferencing. This link is also able to transfer computer aided design (CAD) files for the manufacturing of parts on sight. This data link was key in developing the Minehound light mounts. The high demand of the light mounts exceeded the Ex Lab capabilities. Therefore, the lab sent the file back CONUS where REF established a contract with the Department of Energy (DoE), Kansas City facility, to produce 200 light mounts (M. Hudson, email to author, April 25, 2017). This example shows the Army currently possesses the capability to manufacture parts in multiple locations. The next step is to increase manufacturing capabilities at the point of need.

An example of the Ex Labs assisting the REF with executing their mission of rapidly providing material solutions to the warfighter is the development of a valve stem cover for Mine Resistant Ambush Protective vehicles (MRAP). A unit approached the lab to solve a problem of rocks and debris damaging the valve stem on MRAP wheels. The damage to the valve stem caused wheels to deflate during operations. After five design interactions the final protective metal cover that could easily attach to existing wheel hardware was created. Although AM processes were used to design the protective cover, the final product was manufactured in theater using CNC machines. Although this example highlights the prototyping advantages of additive manufacturing, it also demonstrates how other advance manufacturing processes such as CNC machines can augment 3D printing to develop a comprehensive distributed manufacturing concept.

During discussion with the MRAP Project Manager it was discovered that a wheel redesign effort was underway to fix the deflation issue. However, that effort was expected to take a year before replacement wheels would be fully implemented fielded while the protective cover development took less than five weeks (Asclipiadis 2014). Therefore, Ex Lab was requested to continue implementing fielding the protective covers until redesigned wheels would be fielded. Similar to the Minehound light mounts, demand for the MRAP valve stem protective covers quickly overwhelmed the Ex Lab only CNC machine. REF cooperated with the forward deployed RDECOM's Field Assistance in Science and Technology (FAST) center to produce 100 protective covers (Asclipiadis 2014).

These historical examples show how AM has been leveraged to fill an operational gap. Both the Minehound light mounts and MRAP valve stem protective cover prove that the Army concept of manufacturing at the point of need is practical. Not only is this concept feasible, in the case of the valve stem cover, the distributed manufacturing concept was quicker than using the current acquisition process. Furthermore, the valve cover example demonstrates that each manufacturing location does not need to have the capability to produce every part in the desired quantities. With a distributed manufacturing network, another facility can be leveraged to meet production goals.

F. THE ARMY'S RESEARCH OF DISTRIBUTED MANUFACTURING TECHNOLOGIES

Making science for manufacturing at the point of need an ERA shows the focus the Army is placing on their distributed manufacturing capabilities. The Army is approaching this ERA on two fronts – material and manufacturing. Currently, the Army is studying the use of indigenous and recycled resources to provide materials for their distributed manufacturing concept (Pepi, Zander, and Margaret 2017a, 1).

Mobile foundries are a key technology under development for the Army. The concept behind the foundries is that the foundries will melt scrap metal from battle damaged equipment and other discarded metal, making the metal suitable for casting. Casts will be produced using the lost wax or similar melt casting techniques, using sand from the local environment as the cast medium (Pepi, Zander, and Margaret 2017a, 10–14). The Army is investigating how mobile foundries can produce powder metal to repair parts with AM printing technology (Pepi, Zander, and Margaret 2017b, 10-21).

The Army is also studying the use of plastic waste as a printing medium as part of the distributed manufacturing ERA (Pepi, Zander, and Margaret 2017a, 14–22). Meals ready to eat (MRE) bags and water bottles are some of the first Soldier waste materials being recycled to make filament for FDM 3D printers (Pepi, Zander, and Margaret 2017b, 31–35).

G. SUMMARY

The purpose of this chapter was to provide a common understanding of the Army's maintenance and supply concepts that additive manufacturing could impact. The chapter began with an overview of the Army's supply system and how different supply metric interpretations affect operational availability and unit readiness reporting. Next, an introduction to Army maintenance describes current programs available to commanders to maintain operational readiness.

Discussion of manufacturing concepts provides a foundation to build 3D printing and other advanced manufacturing concepts. An exploration of how the Army is using AM to reduce prototyping and production time led to an introduction of the Army's vision of distributed manufacturing.

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III. EFFECTS OF ADDITIVE MANUFACTURING ON THE ARMY SUPPLY SYSTEM

A. INTRODUCTION

The purpose of this chapter is to assess the effects that additive manufacturing may have on unit readiness. Before one can speculate on system effectiveness, there must first be an understanding of the system requirements. One method is to decompose the process into its basic functions. Figure 2 presents the operational readiness hierarchy for Army equipment. This report evaluates the requirements highlighted in yellow.

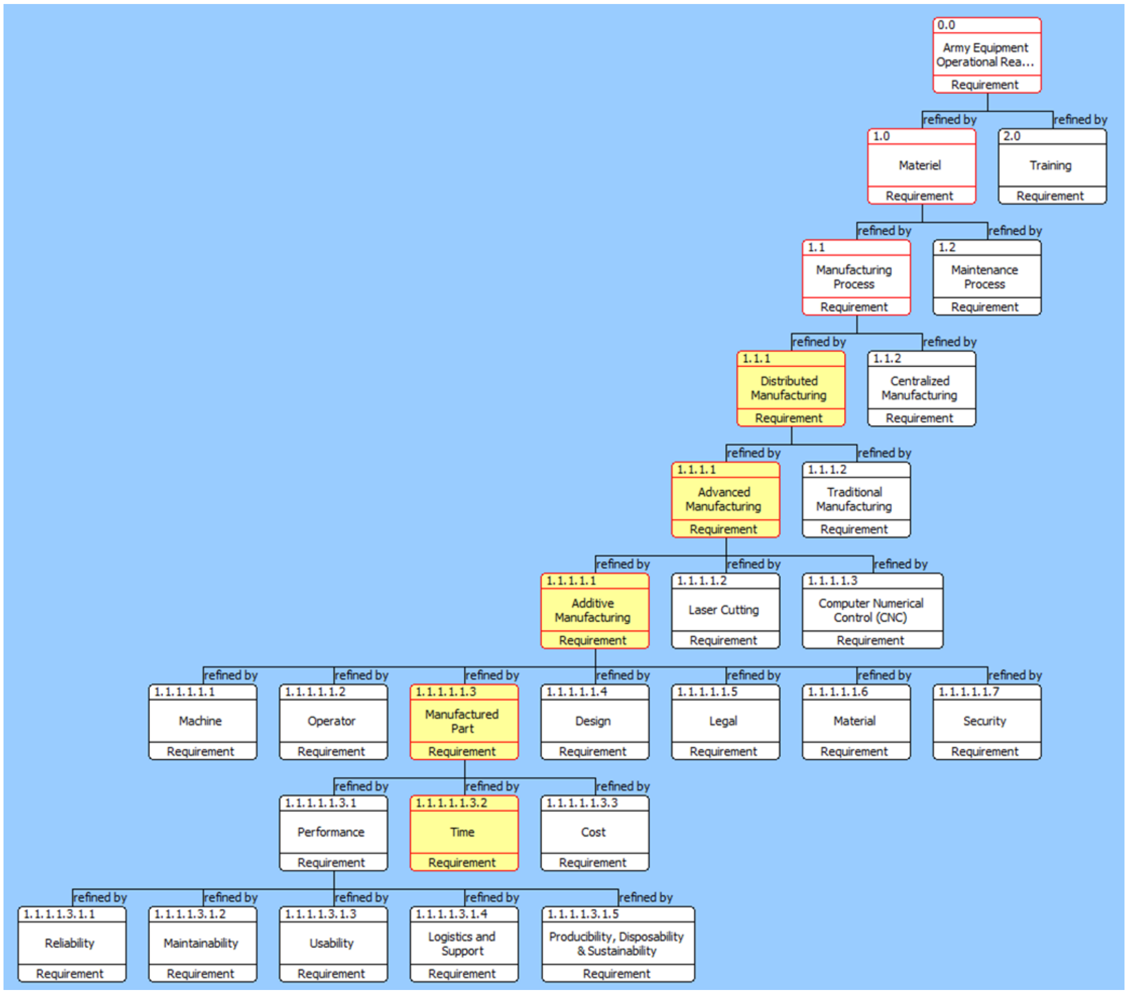


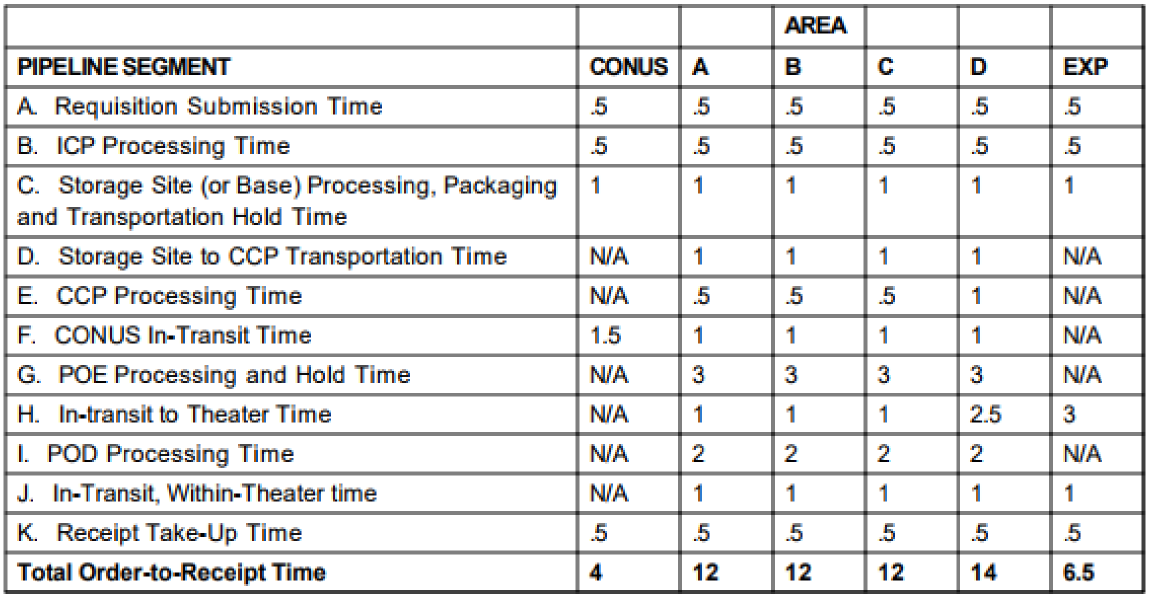
Figure 2. Army Equipment Operational Readiness Requirement Hierarchy

Time is the most basic requirement evaluated in this report. To ensure maximum applicability of results, this report focuses on the time to produce each part. Additional detail regarding performance, which is decomposed into reliability, maintainability, usability, logistical support, producibility, and disposability, is beyond the scope of this work. First evaluated is the efficiency of the supply system which regulates the replacement speed of failed parts. This LDT directly affects the OR rate of Army equipment. This chapter investigates the Time-Definite Delivery (TDD) standards as indicated in Appendix 8 of Department of Defense Supply Chain Materiel Management Regulation (DOD 4140.1-R). Next, the RAND Arroyo Center Report "CWT and RWT Metrics Measure the Performance of the Army's Logistics Chain for Spare Parts" report from early 2000s findings are presented to show the discrepancy between desired supply times and reality. The chapter concludes with additional considerations that may affect the trade space of incorporating distributed manufacturing into the current supply concept.

B. REGULATORY SUPPLY TIME

Time-Definite Delivery standard represent 85 percent of the maximum supply time allowed for items, which are in stock or processed as part of a planned direct-vendor deliveries, to reach its customers (Department of Defense [DOD] 2003, 242). DOD 4140.1-R separates TDD into eleven segments to regulate the delivery of supplies to six geographical areas. Units order emergency repair parts under Category 1 since this category is the quickest supply response category available. Being the quickest supply category it is also the most challenging for the supply chain to accommodate. Presuming Category 1 represents a doninant supply challenge, this report will focus on this category. Table 2 summarizes TDD times for Category 1 requests in numbers of calendar days.

Table 2. Time-Definite Delivery Standards for Category 1 Requisitions Source in Days. Source: DOD (2003).



			AREA			
PIPELINE SEGMENT	**CONUS**	**A**	**B**	**C**	**D**	**EXP**
A. Requisition Submission Time	.5	.5	.5	.5	.5	.5
B. ICP Processing Time	.5	.5	.5	.5	.5	.5
C. Storage Site (or Base) Processing, Packaging and Transportation Hold Time	1	1	1	1	1	1
D. Storage Site to CCP Transportation Time	N/A	1	1	1	1	N/A
E. CCP Processing Time	N/A	.5	.5	.5	1	N/A
F. CONUS In-Transit Time	1.5	1	1	1	1	N/A
G. POE Processing and Hold Time	N/A	3	3	3	3	N/A
H. In-transit to Theater Time	N/A	1	1	1	2.5	3
I. POD Processing Time	N/A	2	2	2	2	N/A
J. In-Transit, Within-Theater time	N/A	1	1	1	1	1
K. Receipt Take-Up Time	.5	.5	.5	.5	.5	.5
Total Order-to-Receipt Time	**4**	**12**	**12**	**12**	**14**	**6.5**

DOD regulation 4140.1-R defines the "area" portion of Table 2 as the geographical location of the customer. CONUS is anywhere in the continental United States. Area A is limited to locations in the vicinity of Alaska, North Atlantic, and the Caribbean to include Guantanamo Bay, Cuba, and Puerto Rico. Northern Europe and the United Kingdom make up Area B. Area C includes locations near Japan, Korea, Guam and in the Western Mediterranean. Area D is the "hard lift areas" which include low used areas of Alaska and Japan, Indian Ocean, New Zealand, Singapore, Greece, Turkey, South West Asia, Kuwait, Bahrain, Oman, and Israel. Finally, express service (EXP) represents any OCONUS location that utilizes commercial door-to-door transportation.

Table 2 briefly outlines each segment of the supply pipeline. Pipeline segment A refers to the allowed time for the customer's local supply support activity (SSA) to submit any requisition the SSA is unable to fulfill. Segment B is the additional time that the inventory control point (ICP) has to process the request. The storage site has until the end of segment C to package and ship the requested part. The first three segment times are independent of the part's final destination.

Container consolidation points (CCPs) are not used for CONUS movements or as part of commercial transit moves. Therefore, delivery times for segment D and E to CONUS or express service locations are not applicable. Segment F is the time standard for CONUS in-transit time (DOD 2003, 245). Segment G, H, and I are the allowed time for port processing and storage and transit between the port of embarkation (POE) and port of debarkation (POD) (DOD 2003, 245). Segment J provided the time standard for intra-theater transportation. Finally, segment K is the standard time that the supporting SSA has to process the received repair part.

The RAND corporation conducted a report of customer wait time (CWT) and requisition wait time (RWT) using early turn-of-the-century data. This report revealed the average RWT for CONUS Army units in January 2003 was 13 days; more than three times the standard established in DOD 4140.1-R. Between 1999 and 2002, Fort Bragg showed improvement in supply time by reducing the CWT from 18 days to 14 days on average. A current evaluation needs to be conducted to see if historical supply processes have continued to improve.

C. POSSIBLE DISTRIBUTED MANUFACTURING LOCATIONS

Figure 3 is a flow diagram of the OCONUS supply transportation process. In this figure, the lettered blue circles represent the pipeline segments defined in Table 2. The star bursts in Figure 3 represent logical locations for distributed manufacturing. Part storage locations, the ICP or the local SSA, are the most obvious locations for distributed manufacturing. A less obvious location is at the POD, which could act as a centralized theater manufacturing location.

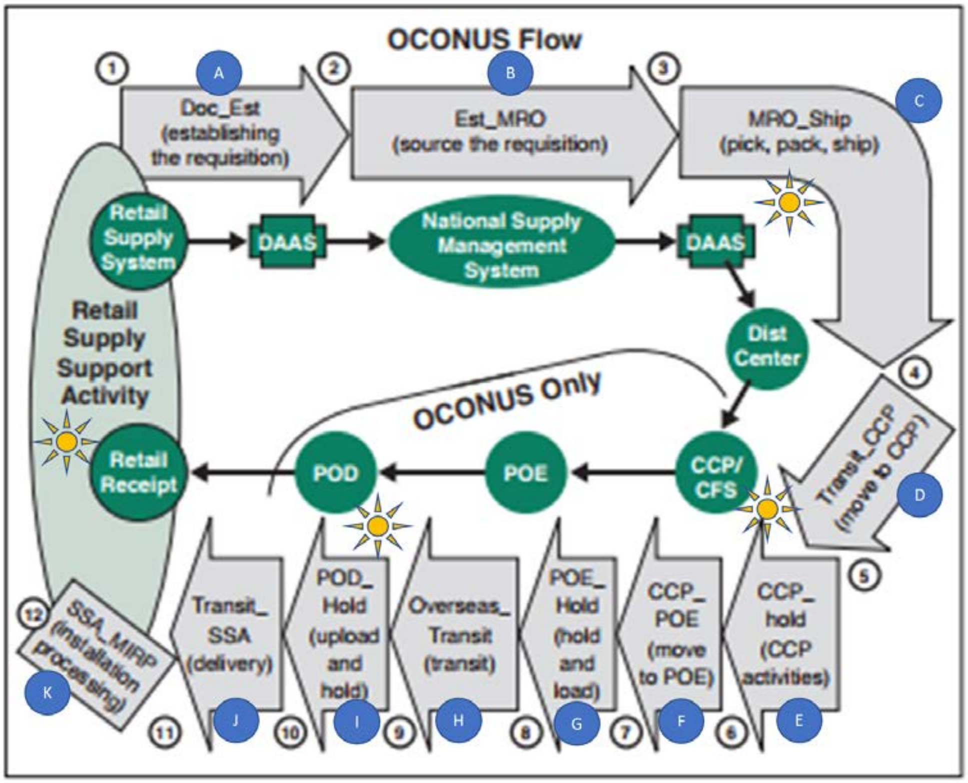


Figure 3. OCONUS Supply Flow Chart. Adapted from RAND (2003).

As seen from the time standards provided in Table 2, the later that one can position the distributed manufacturing process in the supply chain greater the impact distributed manufacturing will have on the supply process. However, cost considerations such as equipment, personnel, and material transportation may make large scale manufacturing capabilities at the supporting maintenance facility or SSA impractical.

Although not part of the supply system, Army labs are currently manufacturing parts and therefore were included in this analysis. The labs could act in place of whole sale/vender manufacturing location. Since it is at the beginning of the supply line, it would only make sense for labs to produce parts on a long back order. It may also work for large complicated parts that are in low demand where stocking these parts is not cost effective. However, in general, using labs as a manufacturing location to provide repair parts is not recommended.

Another location where AM capabilities may be useful is at the ICP, supply pipeline segment B. One drawback to this location is how early in the process this manufacturing facility is located. Being only two days from the beginning of the supply chain leaves little time to manufacture the required part. However, being early in the supply line, this location could serve a larger population, making the return on investment of large industrial grade printers more feasible. However, these are similar capabilities that exist at Army labs, which may be able to provide parts two days earlier in the supply chain.

Another location for a distributed manufacturing facility would be at the CCP or the POD. These two locations are separated by a week along the supply chain as seen in Figure 3. Both of these locations serve multiple customers making it practical to invest in more sophisticated and expensive additive manufacturing equipment. The tradeoff between the CCP and POD is the number of served customers. From this tradeoff analysis; the Army would have to decide if it is worth their return on investment to have large-scale manufacturing capabilities seven to nine days closer to the warfighter. In a combat zone, it may be worth the investment to have AM capabilities at the POD. However, for OCONUS garrison location in area A, B, and C a consolidated manufacturing facility at the CCP may make more sense.

At the unit’s supporting SSA or maintenance facility is the best location to have distributed manufacturing capabilities regarding the largest supply chain time-saving. Locating this capability at the SSA would virtually eliminate the entire supply chain. However, the cost to equip this many locations with additive manufacturing capabilities required to produce the variety of parts needed for that location may not be feasible. However, the investment may be practical if inexpensive parts, similar to those printed as part of the demonstration in this report, could be manufactured at the supporting SSA, and those parts were able to be eliminated from the supply system.

All possible locations to distribute AM processes hinge on a detailed cost benefit analysis. Such an analysis is beyond the scope of this report but is appropriate for follow on research.

D. ADDITIONAL ADDITIVE MANUFACTURING CONSIDERATIONS

Reconsidering the requirements hierarchy presented in Figure 2, numerous requirements are considered. This report focuses on the time aspect of manufacturing the part (1.1.1.1.1.3.2) and the implementation of distributed manufacturing has on the supply timeline. The other primary considerations that affect the manufactured part are cost and performance. Multiple works have provided in-depth research on cost implications of additive manufacturing. These studies have included cost per printed mass by the material. There are also multiple cost-benefit analyses relating the cost of AM produced parts to those that use more traditional manufacturing processes.

Few works have evaluated the full performance spectrum of additively manufactured parts. However, part performance has a significant impact on OR rates. Once again, the underlining concept is time. For example, reliability is often thought of as life expectancy. Blanchard and Fabrycky define reliability as the probability that a part will perform its desired function for a given amount of time (Blanchard and Fabrycky 2011, 363). Simply put, the more reliable the part, the longer the part will last. An improvement in reliability increases the MTBM of the system which, in turn, increases the system's availability and OR rate. This additional aspect of reliability increases the trade space when considering implementing AM processes.

Using Blanchard and Fabrycky's A_O equation $MTBM/(MDT + MTBM)$ in concert with multiple manufacturing locations discussed in the previous section a general relationship between part reliability can be determined (Blanchard and Fabrycky 2011, 427). To use this equation as a surrogate for part reliability an assumption that the evaluated part does not receive maintenance must be made. This means that the part is not serviced to prolong life and when the part fails, the part is replaced instead of being repaired. Using this assumption, the MTBM equals the mean time between failures.

Figure 4 graphs percentage of MTMB that an AM part must meet compared to a similar part received through the supply chain. These calculations use the supply time discussed earlier in this chapter. Logistic delay time uses these supply times. Administrative delay time was assumed to be three days for all supply transactions.

Finally, the total MDT for all AM parts uses two additional manufacturing days in the calculations. Table 3 shows the values used for supply areas A, B, and C in the operational availability calculations to calculate A_O of 0.90.

Table 3. Relative Reliability of Additive Manufactured Parts

	Area A, B, C				
	DoD 4140.1-R	AM @ C	AM @ E	AM @ I	AM @ SSA
MTBM	135	135	126	58	45
MDT	15	15	14	6.5	5
ADT	3	3	3	3	3
LDT	12	10	9	1.5	0
AM Time	0	2	2	2	2
Ao	0.90	0.90	0.90	0.90	0.90
Percent Change in MTBM	100.00%	100.00%	93.33%	42.96%	33.33%

Figure 4 represented the same calculation performed in Table 3 for all supply areas and suggested distributed manufacturing location. From these graphs, it is notable that the MTBM for AM parts manufactured at a given point in the supply system is always the same percentage of a similar part requisitioned thought the whole supply chain. This data suggests that the reliability of a 3D printed part only has to be the ratio of MDT for the AM part versus the non-AM part in order to not affect the A_O.

Figure 4. Required Relative Reliability of Additively Manufactured Parts

E. SUMMARY

This chapter evaluated the idealized supply system and compared those requisition times to historical data. It is likely that the proposed AM location in this chapter will improve supply times more than portrayed as the improvements were based on regulatory times rather than historic times. Using current time would be the best evaluation and should be conducted when data becomes available. The chapter concluded with an evaluation of other AM considerations.

IV. TEST RESULTS AND IMPLICATIONS

A. INTRODUCTION

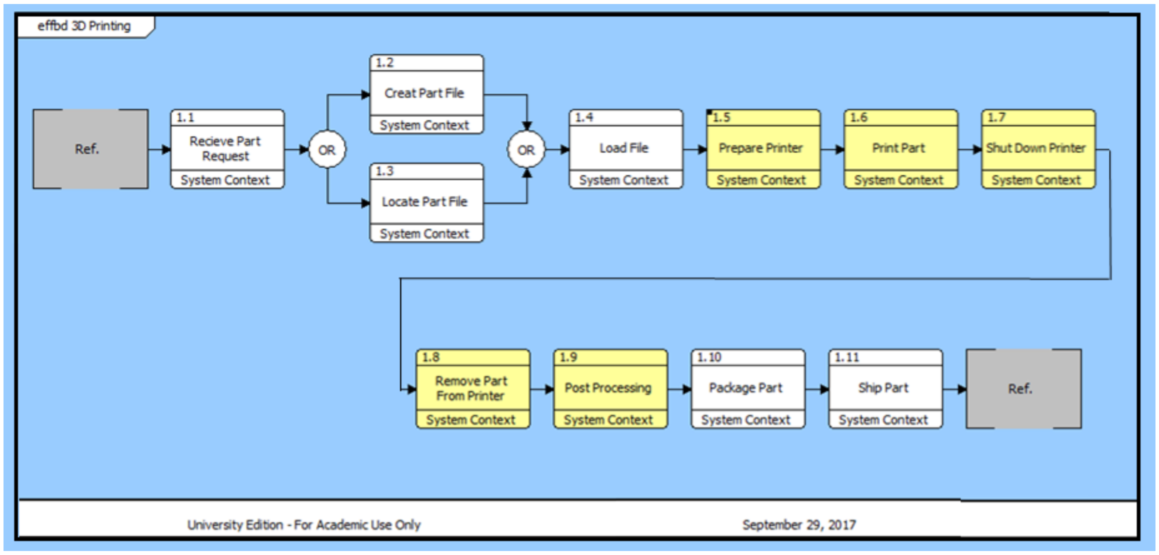
The purpose of the experiment portion of this report is to evaluate different factors of the additive manufacturing process times. Specifically, this test looks at how manufacturing time varies between machine and material for the same additive manufacturing types, in this case, FDM. This test also investigates the time required to execute various steps of the 3D printing process.

This chapter begins with a description of the test approach and setup, followed by review of the test results. Finally, the test results are discussed looking at not only time implications but how the change in supply time affects operational readiness of equipment.

B. TEST APPROACH

The additive manufacturing process consists of 11 steps. Figure 5 presents the functional block diagram depicting these steps. The steps highlighted in yellow depict the steps evaluated in this test. Several steps are not assessed. The first step, receive a part request, is excluded from the experiment since this step is believed to be the same regardless of the manufacturing type. For the same reason, steps 10 and 11, package parts and ship parts, are also omitted from testing. Step two, create a part file, is more relevant to the part design rather than to manufacturing, and will not be evaluated during this test. This step is being evaluated as one of the Army's three certification areas for additive manufacturing and is beyond the scope of this report.

The final two steps of the additive manufacturing process not being evaluated are locate the part file and load file. Since the organization's database structure dictates the efficiency of locating a part file, one can omit this step from testing. Similarly, the load file step is beyond the scope of this report since the connection/network between the database and printer regulates the speed that files can transfer.



This functional flow block diagram illustrates the processes required to produce an additively manufactured part. The highlighted functions are primary functions being elevated during testing.

Figure 5. Additive Manufacturing Functional Flow Block Diagram

Prepare printer (1.5) is the first step of the additive manufacturing process being evaluated. Printer preparation includes loading the print material, build plate preparation, and warming up the extrusion nozzle and build chamber. However, since the materials do not change between each print, loading of the filament is not required each time. Similarly, after leveling the build plate and properly treating the surface, the build plate only requires occasional attention. Thus, these actions are tracked as needed and not by print. Therefore, the prepare printer step only includes the warm-up period for both the extruder and build chamber along with returning the printer head to the home position.

The print part step (1.6) investigates two timed processes: the estimated time provided by the printer software and the actual printing time. This test also investigates the time required to remove the part from the build plate. Since this test only uses plastic building materials, one expects this step will be minimal compared to the print time. However, removing metal parts from metal build plates may take considerable effort. Similarly, the evaluation of post-processing time is expected to be minimal due to the snap off support use by the printer software. However, depending on the required surface finish of the parts, material, and printing method, post-processing time could be significant.

Finally, the relatively short duration of this experiment reduces the requirement for preventive printer maintenance. Therefore, this test ignores preventive maintenance but, includes corrective maintenance time. Additionally, new parts are printed to replace any bad prints. The test will record the time spent printing bad prints and include those times separately in the results.

C. TEST SETUP

The test uses two FDM type printers—a MakerBot Z72 Replicator and a Markforged Mark Two. Each printer will print in two materials. The MakerBot printer will use MakerBot true blue polylactic acid (PLA) lot number 83800 and MakerBot slate grey tough PLA lot number 101974. PLA and Tough PLA marketed by MakerBot are being used for this test since they are the only two materials that MakerBot suggests using with the MakerBot Z72 Replicator. The colors are chosen based on available on-hand quantities required for the experiment. These choices are reflected in Table 4.

As shown in Table 4 the Mark Two printer use Onyx manufacture's code FFF F-MF-0001, and Onyx impregnated with carbon fiber manufacture's code CFF F-FG-005 during testing. The Mark Two printer is capable of printing in Onyx and nylon. Onyx, a micro-carbon fiber reinforced nylon, is stiffer than nylon providing a better comparison to PLA (Scott 2016). Also, Onyx required little post processing which is one of the evaluated steps in the 3D printing process. The randomly selected fiber used to impregnate the printed part is carbon fiber. Other options were fiberglass or Kevlar. One would not expect that the fiber choice would have discernable effect on testing results. This test could be reproduced looking specifically at the printing implications of different fibers.

The software used to read the provided stereolithography (stl) files for the Z72 Replicator, and Mark Two printer are the MakerBot Printer and Eiger software as indicated in Table 4. This test will use the MakerBot Printer software since it is compatible with both PLA and Tough PLA printer heads, unlike the MakerBot Desktop software that is only compatible with the PLA printer head. Appendix A contains the software setting for each printer and part combination.

Table 4. Test Printer, Software and Material Combination

Printer	Software	Material		
		Type	**Color**	**Identification**
MakerBot Z72 Replicator	MakerBot Printer	PLA	True Blue	Lot No. 83800
MakerBot Z72 Replicator	MakerBot Printer	Tough PLA	Slate Grey	Lot No. 101974
Markforged Mark Two	Eiger	Onyx	NA	FFF F-MF-0001
Markforged Mark Two	Eiger	Carbon Fiber	NA	CFF F-FG-0005

The parts printed for this test are a subset of PackBot parts provided by the Army. The PackBot is an iRobot designed robot the Army is using to demonstrate the validity of creating repair parts for combat equipment using additive manufacturing. The articles chosen for this experiment are the PackBot top and bottom claw, claw holder and small flipper wheel with a spacer. The top and bottom claw are mirror-imaged parts that are printed individually and as a set. These parts provide an opportunity to evaluate the time required to postprocess sets of parts that have to function together.

The small flipper wheel with a spacer is printed on a single build plate. The part is chosen to demonstrate manufacturing of parts with tolerances that must fit together. Finally, the claw holder was chosen due to the balance between print time and required support that may affect post-processing time.

After the test parts are selected, trial prints are created to ensure operator proficiency, and reducing learning curve effects on manufacturing times. The trial prints are also used to adjust printer settings to provide the best quality part. One would expect the Army to follow a similar process to develop universal standard settings for each 3D printer and printed part combination.

Microsoft Excel’s random number generator will select the manufacturing order. This random ordering will reduce the effects of learning curve bias and environmental factors on the test. The use of cameras with time displays will record step 1.5 through 1.8

of the AM process, to ensure accurate recording of events since lab personnel may not be present for the duration of each test event. The final tested step of the process, post processing, will be timed using a stopwatch.

D. TEST RESULTS

1. Prepare Printer (1.5)

The evaluation of two steps represents the total printer preparation time (1.5). The first evaluation was regarding filament changes. Filament changes were only required on the MakerBot taking a total of 3:16:13 (the duration of this report will use this notation meaning 3 hours, 16 minutes and 13 seconds). Based on the randomly selected printing order, the filament changed 15 times to manufacture the 30 parts on the MakerBot. The filament changes ranged between 00:09:29 and 0:18:03 with an average of 0:13:05 and a standard deviation of 0:01:56. Filament changes represents 2.01 percent of the total manufacturing time on the MakerBot Z 72 Replicator, the only printer that required filament changes. The data for all filament changes is summarized in Appendix C, Table 11.

The second evaluation of printer preparation time (1.5) was printer warm-up. The warm-up time for the MakerBot required the heating of both the extrusion nozzle and the build chamber. These actions took an average of 0:05:14 ranging between 0:03:27 and 0:11:08. The Mark Two did not require the build chamber to be heated it only had to heat the filament and fiber nozzle when used. On average the Mark Two took 0:03:00 to preheat, approximately 0:02:14 less time than the MakerBot. The heating of both Mark Two nozzle required to print with carbon fiber took an average of 0:03:01 ranging between 0:02:17 and 0:04:10. The heating of just the filament nozzle required for Onyx prints took an average of 0:02:58 ranging between 0:02:22 and 0:03:22.

The standard deviation in the printer warm-up time for the Maker Bot was 0:1:49, over five times the 0:00:19 standard deviation of the Mark Two. The MakerBot larger standard deviation implies there is more variation in the MakerBot warm-up time than the Mark Two. We believe this variation is due to the printer having to overcome the ambient temperature of the room while preheating the build chamber.

The total time spent preheating the printers to manufacture the 60 test articles was 5:50:33. This time is equivalent to just over 1.7 percent of the total manufacturing time. The combined preparation time for both printers took 9:06:46. This is approximately 2.78 percent of the manufacturing time.

2. Print Part (1.6)

The print part step (1.6) in the test evaluates the software's estimate to print the parts and the actual time to print the parts. Although both the MakerBot Printer and Eiger software provided identical estimates for each part/material combination, they overestimated the actual print times. Table 5 shows the estimated printing time versus the actual print times. Table 14 in Appendix C contains a similar table, but shows the relationship between the part, software, and material.

Table 5. Estimated Versus Actual Print Time by Software and Material

Software	Material	Avg. Printing Time		Difference	% Over Estimate
		Estimated	Actual (Avg.)		
MakerBot Printer	PLA	5:07:48	4:45:26	0:22:22	7.84%
MakerBot Printer	Tough PLA	5:03:24	4:40:38	0:22:46	8.11%
Eiger	Carbon Fiber	7:38:36	6:36:11	1:02:25	15.75%
Eiger	Onyx	4:01:48	3:39:00	0:22:48	10.41%

By averaging the print time of the machines and materials, one can better understand the effect that the articles have on the print time. This value provides an average time it took to print that specific part regardless of the printer or material used. Likewise, to evaluate the effect that the printer, software and material combination has on print time, the average printer/material combination print time is used. This value provides an average time it took for the printer to print all test articles in a given material.

The printing time for the PLA, tough PLA and Onyx is similar. The printing time for carbon fiber was much longer, as seen in Figure 6. The longer print time for carbon fiber is primarily due to maximizing the amount of carbon fiber in the printed part, making the infill nearly 100 percent, while the other materials printed with a 50 percent infill.

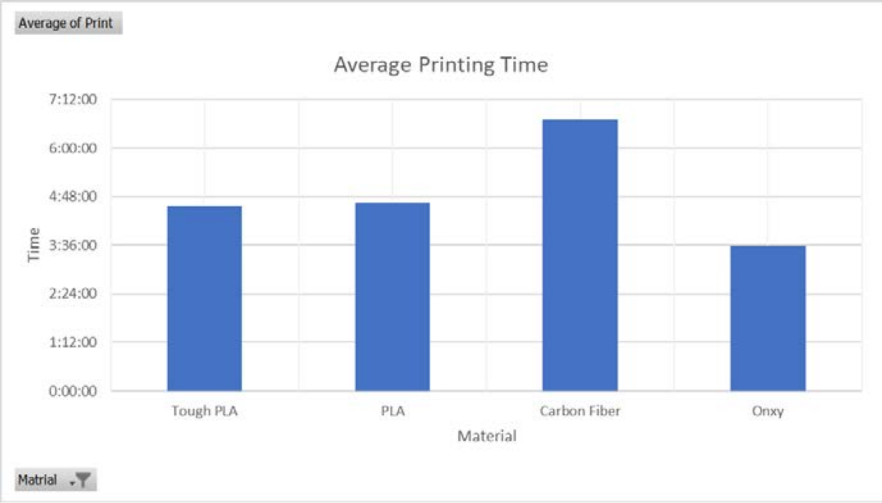


Figure 6. Average Print Time of Parts Shown by Material

To help eliminate the bias due to the fill rates, the average time to print each gram of the part was calculated. Doing this, the Onyx and carbon fiber normalizes but takes approximately three minutes longer per gram to print than the PLA or tough PLA. Both Figure 7 and Table 13 (Appendix C) show these results.

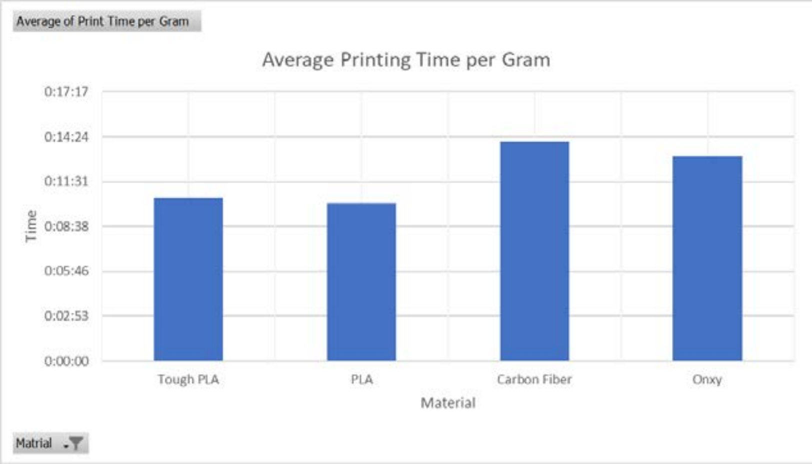


Figure 7. Average Print Time per Gram Shown by Material

Evaluating the parts averaged over all of the printers and materials, the flipper wheel with spacer took between 40 and 55 minutes less time to print than the other individual parts did. This is shown in Figure 8. Most of the reduced time is due to the reduced mass of the small flipper wheel and spacer.

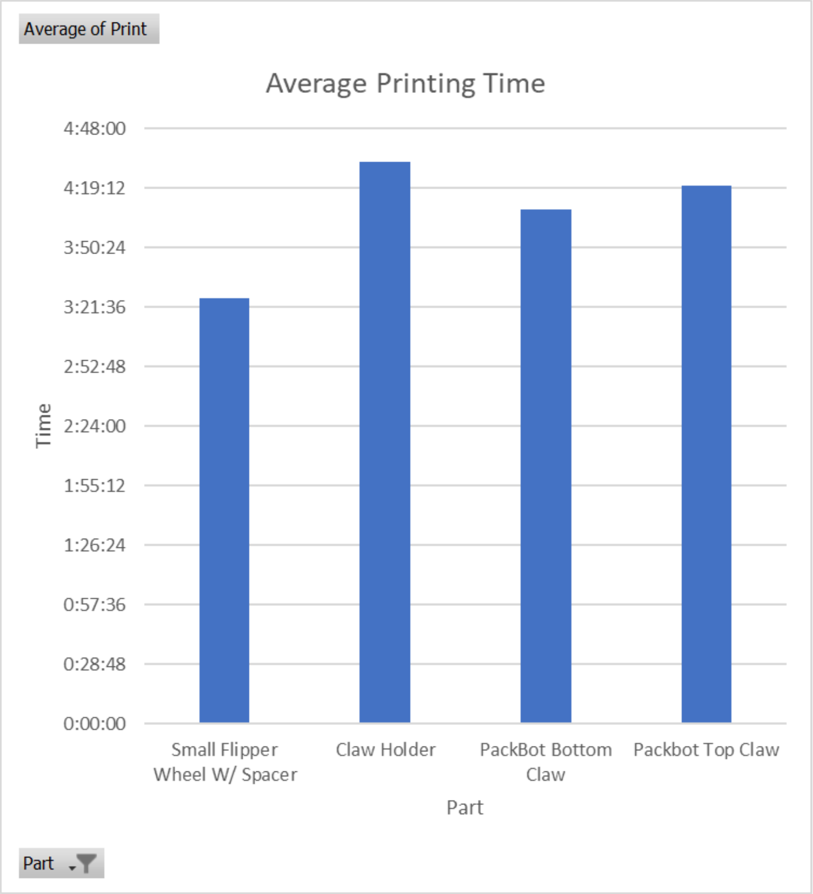


Figure 8. Average Printing Time of Individual Parts

Figure 9 shows the print time per gram of each part. One may notice that the small flipper wheel and spacer are within a minute of the time required to print either claw, while the claw holder takes approximately a minute less time to print each gram than any other part. One might expect the printing time per gram to vary between materials or printers. However, this time variation between parts may imply that a part's geometry influences print time. This demonstration lacks data to confirm this suspicion and should be evaluated in future studies.

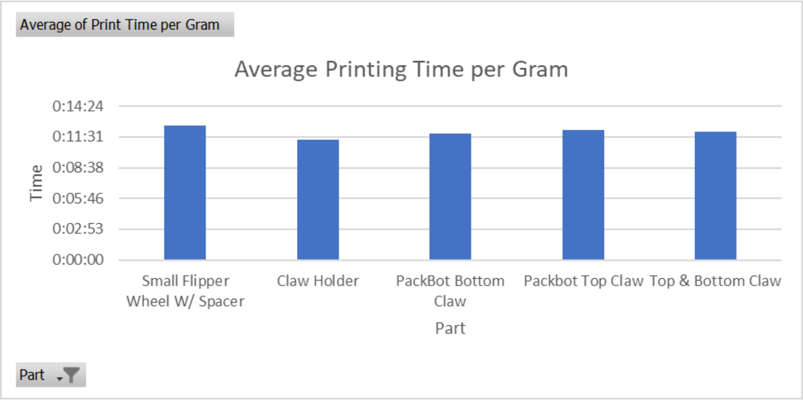


Figure 9. Average Printing Time of Parts per Gram

Averaging the part's print time across the printers and materials reveals the effect that printers and materials have on printing time regardless of the article's geometry and placement on the build plate. The averages shown in Figure 10 reveals that carbon fiber parts take the longest to print. This extended time once again may be the result of the fiber parts being printed with a denser infill.

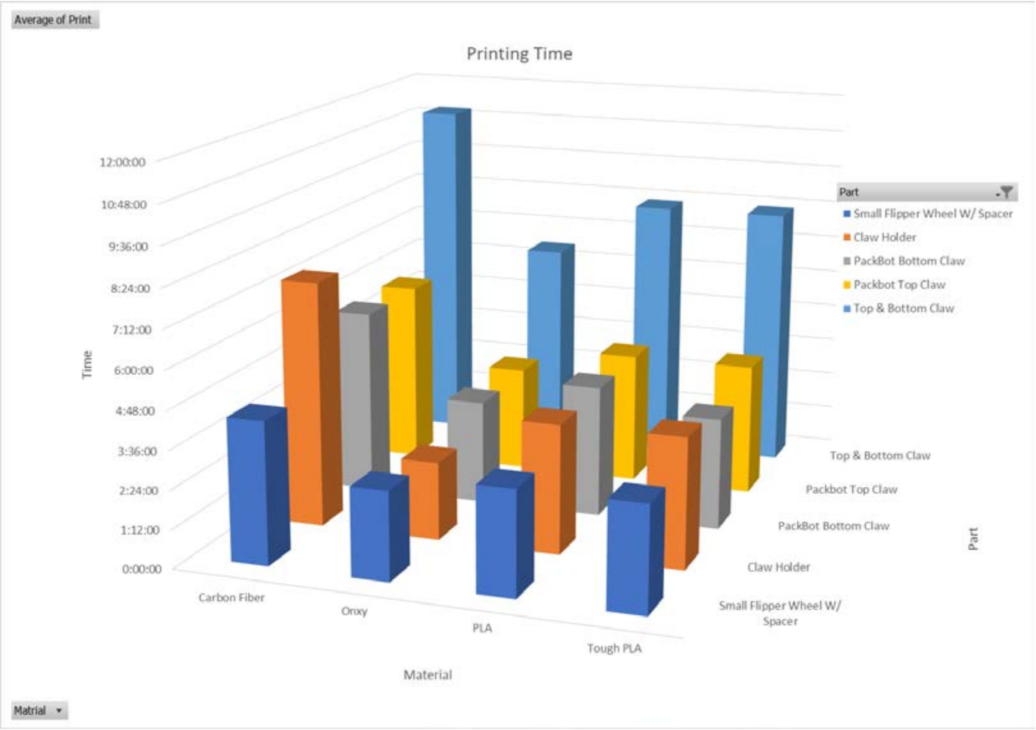


Figure 10. Average Printing Time

To normalize the effect of infill rates, the average times per gram was calculated. Figure 11 displays the results of these calculations, revealing that printing time is a function of the printer and not of the material.

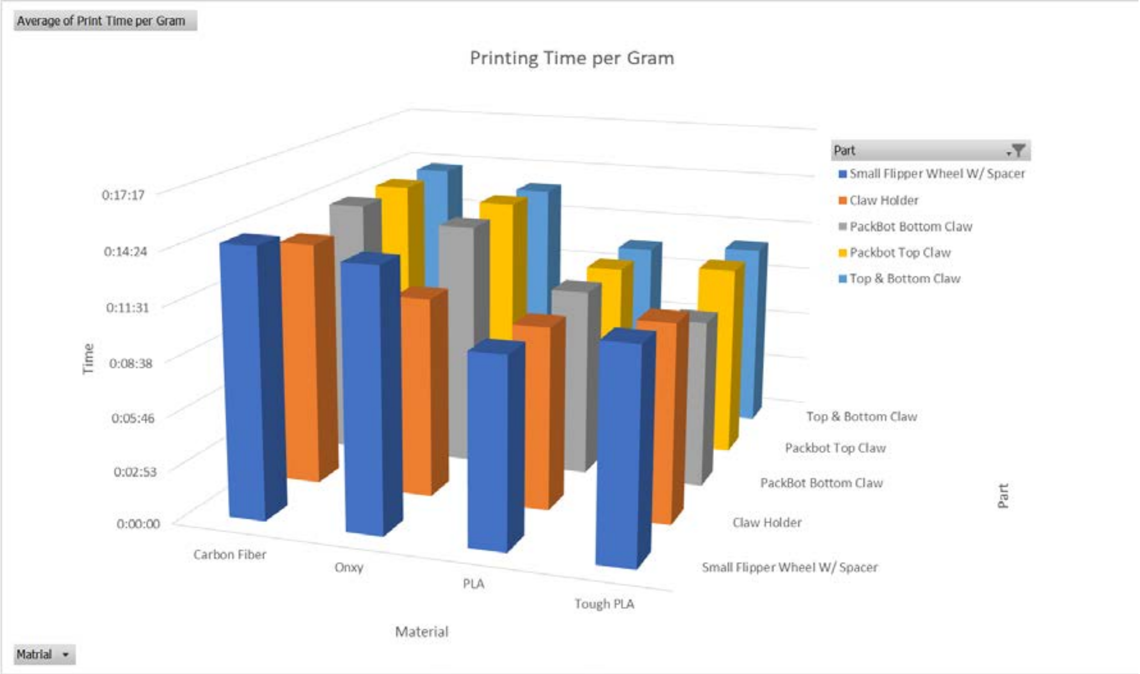


Figure 11. Average Printing Time per Gram

Possibly the most surprising result is the difference between the top and bottom claw that are simple mirrored-images of each other. First, the estimated mass of the top claw is 0.17 grams greater than the bottom claw with the printed mass being 0.25 grams greater. The average time per gram to print the top claw is 16 seconds longer than it is to print the bottom claw. Since the geometry is the same, one could conclude that the extended print time is due to the part orientation on the build plate or an error in the software. Once again, this test lacks the data required to confirm these hypotheses.

A closer evaluation of the data reveals the trend of the top claw taking longer to print per gram is only noticeable for the MakerBot printer printing in tough PLA. In this case, the top claw takes a full minute longer to print one gram than the bottom claw does. PLA and carbon fiber printed claw only vary by one second and the Onyx varies by eight seconds. Further testing is required to understand how the change between PLA and tough PLA make such a noticeable difference in printing times.

To evaluate if printing multiple parts in a single build affects printing time, the top and bottom claw were printed individually and simultaneously on a build plate. The print time for the simultaneously printed claws was divided in half to reflect the time to print the claws individually. These averages are shown in Figure 12. From this figure, it appears that including multiple prints on a single build plate does not affect the single print time for that part.

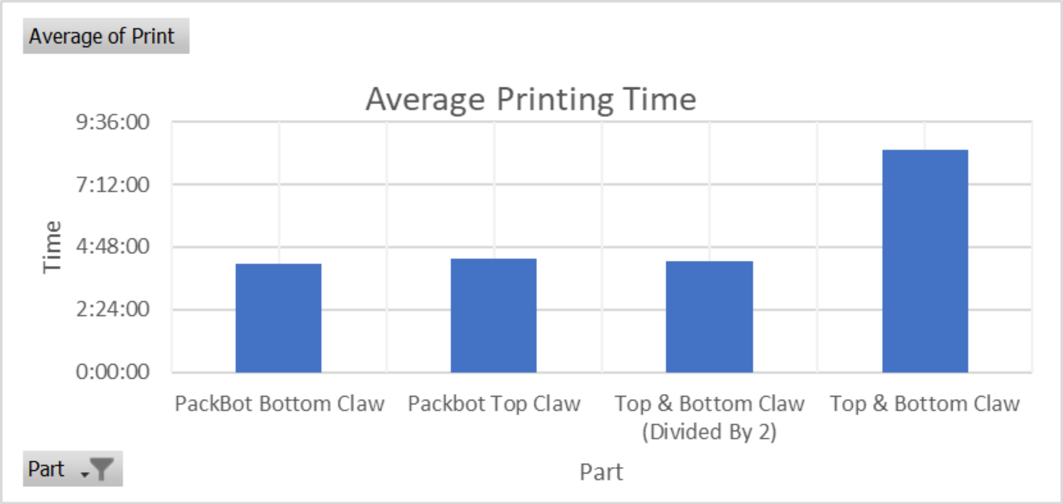


Figure 12. Average Claw Printing Time

3. Clear Printer (1.7, 1.8)

The steps required to clear the printer included removing the build plate from the build chamber, removing the part from the build place, followed by returning the build plate to the build chamber. To access the build chamber on the MakerBot the door first must be pressed in to release the magnetic latch before swinging the door open. Two latches in front of the elevation platform secure the build plate. Rotating these latches releases the build plate from the build chamber. A paint scraper is then used to release the part from the build plate. The build plate is reinserted in reverse order to the build chamber rendering the printer ready for the next build.

This process is similar with the Mark Two. However, the front opens upward and is not secured by latches. The build plate is secured to the elevating platform with magnets making it able to be removed by simply lifting the build plate off of the elevating platform. Unlike the MakerBot, the Mark Two does not include a container that the printer can be used to purge the extruder nozzle. Therefore, the Mark Two purges along the back edge of the build plate. The removal of this material is necessary when clearing the printer. One additional step required with the Mark Two is to tap “Clear Bed” on the printer display. This step notifies the printer that the build plate is free from obstructions and is ready for the next print.

On average the PLA prints on the MakerBot and both materials used on the Mark Two required 23 seconds to remove. It took 27 seconds to perform the same function with the tough PLA on the MakerBot. Removing the parts from the build plate was conducted in the same random order that the parts were built to eliminate the learning curve bias. The average time to remove specific parts from the printers averaged 24 seconds plus or minus one second. The only exception to this was for the top and bottom claw printed on the same build plate. It took 27 seconds to remove printed pairs from the build plate. Removing the pair of parts averaged less than 13 seconds per part. Printing both of these parts on one build plate saves approximately 10 seconds per part, an insignificant amount compared to the total manufacture time.

4. Post Processing

Multiple methods are available to post process the tested parts such as advanced manufacturing processes, power tool or hand tools. To decide which methods would be leveraged for post processing requires careful consideration. First is the relative cost of the post-processing method. To make distributed manufacturing palatable to the Army, the investment cost must remain low. Therefore, using expensive advance manufacturing equipment is not recommended unless absolutely required. The next consideration is finished part tolerances. In the application of the chosen parts, the finished part dimensions are not critical as long as the top and bottom claws relatively match and the small flipper wheel space can fit inside the wheel. This requirement once again eliminates the need for accurate post-processing tools such as CNC machines, mills or lathes. Finally, the soft polymer parts do not require power tools. Using power tools may produce enough heat to damage the parts. Thus, all parts were post processed using only hand tools.

The use of pliers assisted with snapping off the rafts used to secure the PLA and tough PLA to the MakerBot build plate. Pliers were also used to remove support structures from all parts. A utility knife and sandpaper were used to trim edges and shape parts as needed. The knife was also used to remove some of the support material from the bottom of the claw holders. Finally, the use of a small-angled cutter assisted with removing the raft that was not removed with pliers. Difficulties removing rafts were most common with the tough PLA part, specifically with the small flipper wheel.

Post processing varied greatly with the material. On average the tough PLA took twice as long to post process than PLA, three times longer than carbon fiber and over four times longer than Onyx. Both the PLA and tough PLA had more material to remove than the other material types to the use of the support raft. When averaged across the amount of material removed during post-processing tough PLA took nearly 20 seconds less than either Onyx or carbon fiber and just over twice the minute per gram that it took to post process PLA.

Both Table 12. located in Appendix C, and Figure 13. below shows that the small flipper took the longest to post process at 0:07:43. The next closest time was the claw holder taking 0:06:27, followed by the bottom claw at 0:05:18 and the top claw at 0:05:15. Since the claw holder had to be built on top of a support structure, one may believe this part would take longer to post process. However, the most difficult sections to separate are the edges of the article from the raft. Due to the design of the small flipper wheel and spacer, the part is primarily edges. A summary of the post-processing times can be found in Figure 13.

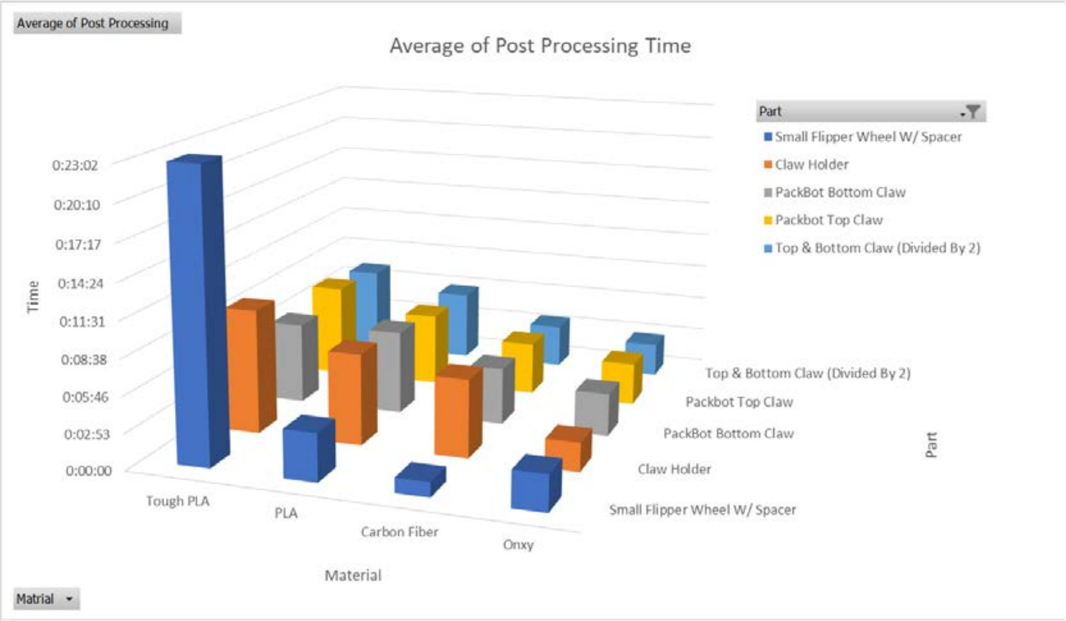


Figure 13. Average Post-Processing Time

5. Total Manufacturing Time

The total manufacturing time is the summation of all the previously discussed additively manufacturing steps. Printer prep (1.5) accounts for less than two percent of total manufacturing time. Post processing (1.9) has a similar portion of the manufacturing time, averaging just over two percent. Clearing the printer (1.8) is the least time-consuming activity, averaging approximately 0.13 percent of the total manufacturing time.

The print part step (1.6) is the most time consuming. On average, it accounts for nearly 96 percent of the total manufacturing time. The percentage of manufacturing time contributed to printing ranges from just less than 94 percent to just more than 97 percent when evaluated by part as seen in Figure 14. The range of printing time is slightly greater, between 93 percent and just over 98 percent, when evaluating the printer or material as shown in Figure 15.

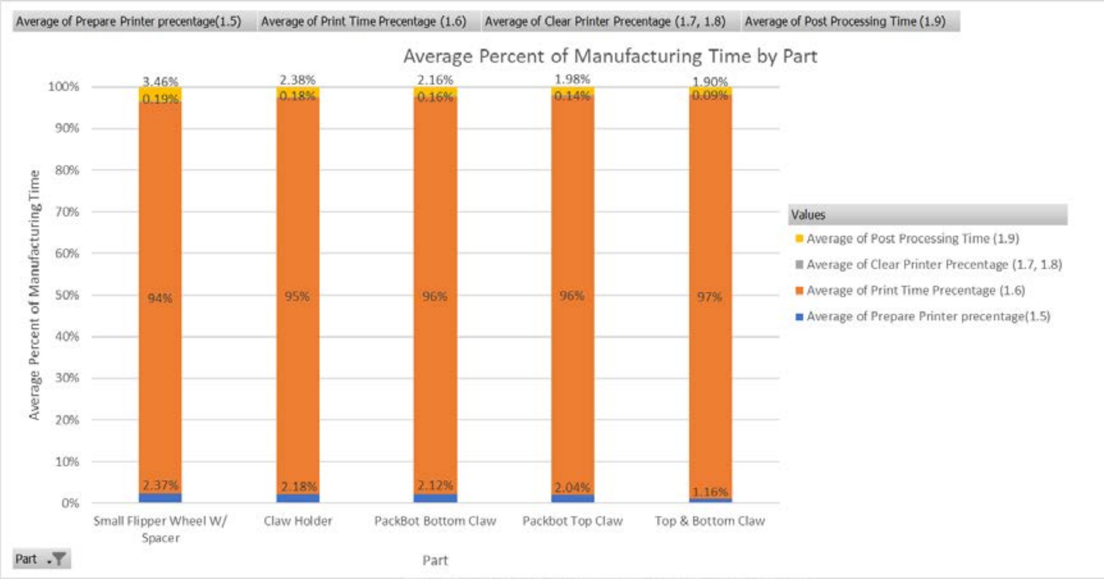


Figure 14. Percentage of Total Manufacturing Time Evaluated by Part

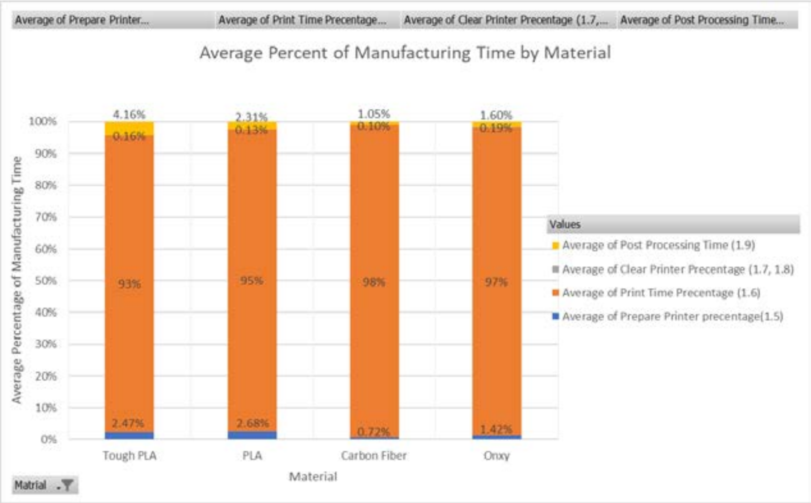


Figure 15. Percentage of Total Manufacturing Time Evaluated by Material

6. Additional Manufacturing Requirements

Several aspects reduce the efficiency of the demonstrated additive manufacturing process. The two primary ones discovered during this test includes failed prints and maintenance issues. The failed prints often resulted in required maintenance but not always. Of the original 60 test parts, 10 percent failed to print correctly the first time. Of the six first-time failed prints, one failed a second time. These failed parts were not included in the above analysis, since they did not complete the entire manufacturing process.

Claw holders were the most likely to fail with two of the original dozen failing to print the first time correctly and with one failing to print the second time correctly. Two of the top claws also failed the first time. The only part that did not fail on the first print was the small flipper wheel and spacer. The Mark Two was most likely to result in failed prints with two-thirds of the first time fails and the only second time fail was on this printer. Each material accounted for half of the first-time failures on their respective printers. Table 6 list the part, printer, material, and failure.

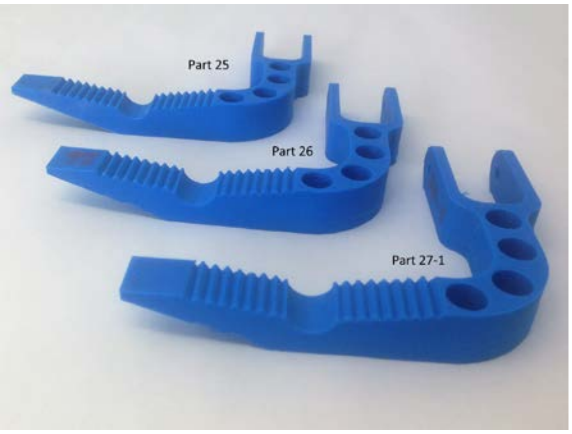
Table 6. Failed Prints

Part No.	Part	Printer	Material	Failure
21	Claw Holder	Mark 2	Carbon Fiber	Four fiber jams, reprint part
21-1	Claw Holder	Mark 2	Carbon Fiber	Massive failure, see photos
24	Claw Holder	Mark 2	Onyx	Bottom layers were pealed from build plate, reapplied glue to build plate
27	Packbot Top Claw	Maker Bot	PLA	Filament slippage due to tangle roll of filament, damaged top of the build, reprinted part
31	Packbot Top Claw	Mark 2	Carbon Fiber	Pulled print from build plate, reprinted part
42	PackBot Bottom Claw	Maker Bot	Tough PLA	Shifted on raft, destroyed during post processing, reprinted part
58	Top & Bottom Claw	Mark 2	Onyx	Pulled print from build plate. replaced build plate

This table provides a list of parts, printer and material combination that failed to correctly print along with the failure.

Part 42, bottom claw printed in tough PLA, which was the 57th print is a unique failure as it printed slightly off center of the raft. It was believed to be a good print. However, during post processing, the claw was unable to be removed from the raft causing damage to the part. Photographs of the offset print and the destroyed part during post processing can be found in Appendix D.

Four other times the printers malfunctioned but did not result in lost products, only loss in time to recognize and correct the issue. The most common issue was jammed fiber nozzle on the Mark Two. The other issue was running out of filament. The only material that ran out during a print job was PLA. The lab tech knew there was not sufficient filament to finish the part but was curious about the effect of running out of filament would have on the final part. In this instance there was no degradation in part quality as seen in Figure 16. The only time that the Mark Two paused due to the low material was caused by a metering issue that occurred during the loading of the carbon fiber. This error caused the printer to believe it was out of fiber when in fact it was not. This issue was corrected by overriding the Mark Two self-metering function.



This figure shows there is no degradation in part quality due to running out of filament while printing part 25.

Figure 16. Comparison between Parts Made without Changing Filaments and Changing Filaments

Table 7 shows the part, printer, and error that resulted in some corrective action or maintenance in the order the error occurred. The lab tech was not experienced with fiber jams when the first one occurred. However, after correcting the issue once, the corrective action time for this fault dropped to just about one-quarter of the time as seen in Table 7.

Table 7. Corrective Action Time

Part No.	Part	Printer	Martial	Error	Corrective action	Corrective Action (H:MM:SS)			Comment
						Start	Finish	Elapsed	
20	Claw Holder	Mark 2	Carbon Fiber	Fiber Jam	Replace fiber nozzle insert	10:54:08	11:14:04	0:19:56	Able to continue print
31	Packbot Top Claw	Mark 2	Carbon Fiber	Fiber Jam	Replace fiber nozzle insert	9:07:33	9:24:21	0:16:48	Had to restart print
25	Packbot Top Claw	Maker Bot	PLA	Out of Filament	Replace filament	12:19:40	12:27:51	0:08:11	Able to continue print
60	Top & Bottom Claw	Mark 2	Onyx	Out of Fiber	Over half a roll of fiber remained, over rode the printer low fiber meter	16:12:19	16:16:05	0:03:46	Able to continue print
21	Claw Holder	Mark 2	Carbon Fiber	Fiber Jam	Replace fiber nozzle insert	9:17:51	9:22:07	0:04:16	Able to continue print
21	Claw Holder	Mark 2	Carbon Fiber	Fiber Jam	Remove jam from nozzle insert	8:19:15	8:22:16	0:03:01	Able to continue print
21	Claw Holder	Mark 2	Carbon Fiber	Fiber Jam	replaced fiber nozzle	11:19:58	11:23:04	0:03:06	Able to continue print
21	Claw Holder	Mark 2	Carbon Fiber	Fiber Jam	replace nose insert, removed print, started new part	12:27:17	12:29:57	0:02:40	Had to restart print
21-1	Claw Holder	Mark 2	Carbon Fiber	Print did not stick to build plate	Washed and reglued build plate, releveled build plate, Reprinted part	14:28:05	14:52:40	0:24:35	Had to restart print
56	Top & Bottom Claw	Mark 2	Carbon Fiber	Fiber Jam	Replace fiber nozzle insert	15:18:04	15:22:24	0:04:20	Able to continue print

This table illustrates the errors that lead to a required action along with the time to perform that corrective action and the result of the corrective action.

E. IMPLICATION OF TEST RESULTS

The above test showed that for FDM 3D printers the printing time accounts for approximately 96 percent of the total manufacturing time. Both the MakerBot Printer and Eiger software over estimates the actual print time but closely predicts the total manufacturing time. The software print estimation can be used as a planning factor for total manufacturing time in the tested cases. Given that print time dominates the total additive manufacturing time, immediate investment should focus on printer quality, rather than printer quantity, training, or pre/post processing improvements.

F. SUMMARY

This chapter tested printing four parts in four materials on two printers to evaluate the effects that parts, materials, and printers have on total additive manufacturing time. The test went one step further and demonstrated the effect printing multiple parts on a single build plate has on total manufacturing time.

The test revealed the part’s physical characteristics played an insignificant role in the printing time when evaluated per gram. Likewise, there is no apparent correlation between material and print time. Furthermore, this test demonstrated that, on average, just over four percent of the total manufacturing time is attributable to functions outside of the printing time. Although this additional time is covered in the software estimation of print time, the machine that requires the most additional manufacturing time was also the machine where the software overestimated print time the least.

To demonstrate the effect of printing multiple parts on a single build plate has on the total manufacturing time, the top and bottom claw were printed on the same build plate and on separate build plates. This evaluation revealed there is no apparent saving on the print time. However, preparing the printer and clearing the printer times were able to be split among the parts. The total time to post process the multiple parts on a single build plate was slightly less per part than during individual build but not by a factor of the number of parts printed. On average, building multiple parts on a single build plate showed no significant difference than printing the parts individually.

This test demonstrated that the most noticeable factor of print time is the machine building the part. Thus, the primary factor in total additive manufacturing time is the printer.

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V. CONCLUSION

A. OVERVIEW

The purpose of this research was to demonstrate the time requirements of additive manufacturing and postulate the effect on operational readiness of incorporate distributed manufacturing capabilities within the supply system. An analysis of distributed manufacturing impact on system maintainability demonstrated the effects that distributed manufacturing has on repair part supply times. The time implications were then used to calculate the acceptable reliability of distributed manufactured parts required to preserve system maintainability. System maintainability factors which pertain specifically to additive manufacturing form the basis for the calculations.

The first chapter introduced the concept of distributed manufacturing and why the Army has determined it to be an essential research area (ERA). Chapter I continued with limitations and methods for research and data collections before concluding with an organization of the report.

The contextual review covered the impact that implementing of distributed manufacturing may have on both the Army supply and maintenance concepts. Most notably, the ability to manufacture repair parts at the point of need could significantly alter current supply times and logistical overhead. Next, the literature review investigated the advanced manufacturing techniques that makes distributed manufacturing a viable option for organizations of all sizes. Although there was a brief description of computer controlled manufacturing processes such as laser cutters and CNC machines, the literature review presented a detailed comparison of additive manufacturing techniques.

Chapter III reviewed the DOD regulatory supply delivery time. This chapter also used a RAND report from 2003, to compare idealized supply time with historical supply times for both CONUS and OCONUS location. Chapter III concluded by considering additional factors that related to the implementation of additive manufactuing within the Army supply system.

Chapter IV explained the methodology for testing additive manufacturing parts to better understand the relationship between print time and total manufactuing time. During testing, four parts were printed with four materials on two machines to evaluate the relationship among all steps of the AM process. As part of this test, two parts were printed both together and individually on the build plate to evaluate possible time implications of combining prints.

B. FINDINGS

This report revealed three primary findings along with confirming that distributed manufacturing location has the potential to affect the current supply system. The three primary findings are

- Required part reliability is a function of MDT.
- Metric to predict total additive manufacturing time is based on estimated printing times.
- Multi-part builds show no advantages.

The first revelation was the ratio between MDT equals the ratio between required part reliability. Therefore, if part A requires a total of 10 days to go through the ordering, receiving and installation process, and part B only requires five days for the same process or half the time, then part B only has to be half as reliable as part A to maintain the same operational availability.

Testing revealed that 96 percent of the total additive manufacturing time is due to printing the part. The remaining time is a result of pre-production time and post-processing time. These relative proportions of time are shown in Figure 17. Since the printing time dominates the AM process, this is where resources such as money, research, personnel, time and d equipment should be concentrated.

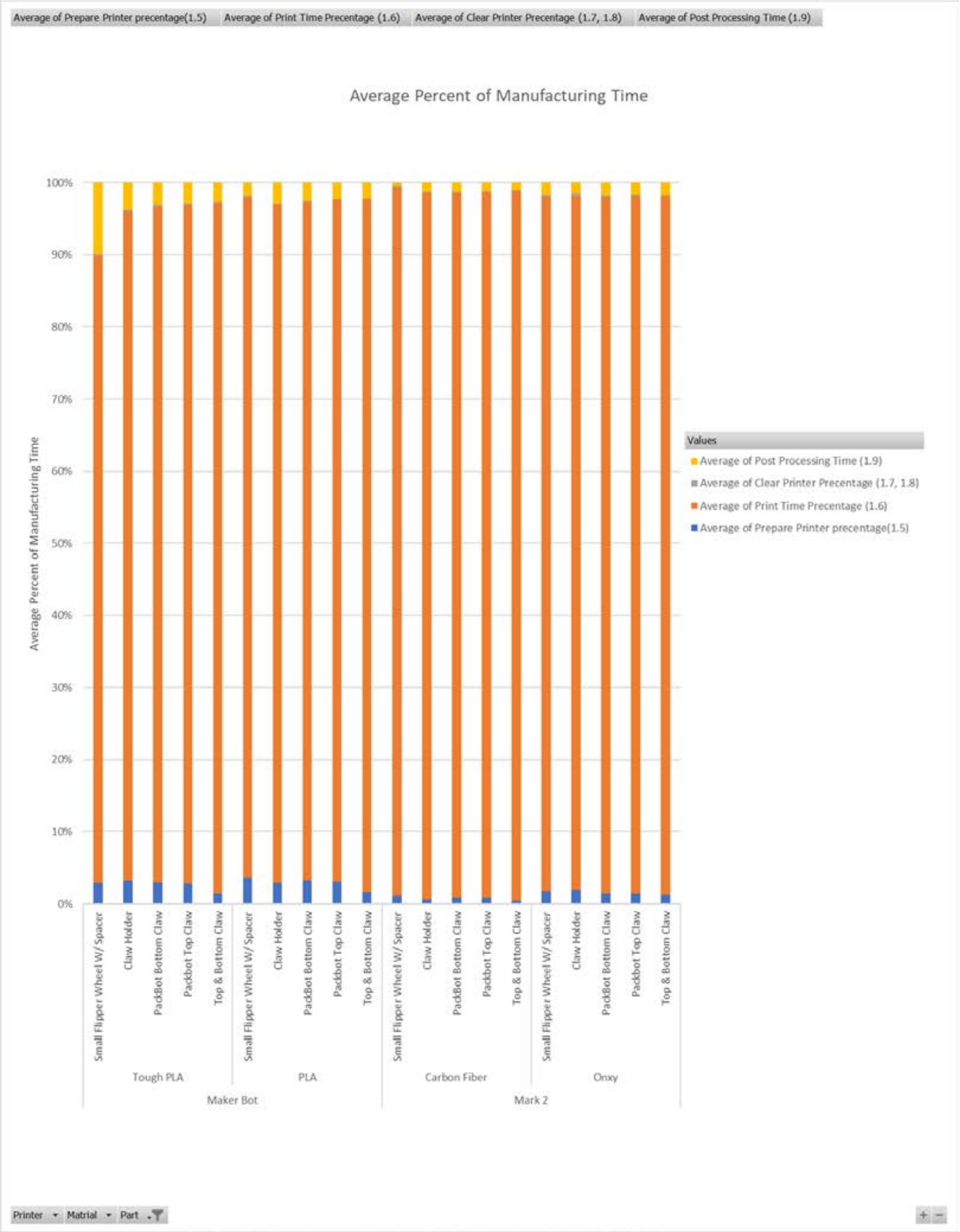

Figure 17. Percentage of Manufacturing Time

The two software programs used in concert with the printers in this test regularly overestimated printing time to the point of nearly encompassing the total manufacturing time. Thus, for this test, the estimated print time would serve as a good rule of thumb of total AM time.

Finally, the test revealed that printing parts together on a single build saves an insignificant amount of manufacturing time over printing the parts individually. When averaged over the total manufacturing time, the time savings does not counter the risk of a printer failure ruining multiple parts during a multiple part print.

These findings can be used by stakeholders at all levels to decide which process is best for the organization. Stakeholders are now able to answer questions like:

- Should the unit wait for the supply system to provide a part or is it better to contact a distributed manufacturing facility for the part?
- If material required to manufacture a given part is unavailable, what is the risk to operational availability if the part is printed in a different material?

C. RECOMMENDATIONS

This report showed that OR rate can be improved by incorporating additive manufacturing capabilities throughout the supply chain, with manufacturing capabilities at the unit potentially having the greatest improvement. The Army should consider providing high-quality FDM printers, with the ability to print with reinforcing materials, to units deployed remotely as a mean to enhance maintain operational readiness. Although this type of printer may not have the capabilities of SLM or SLS type printers, a diminished capability is better than no capability. Finally, based on the finding of this report, printing time dominates the additive manufacturing process. Therefore, it is recommended that the Army utilize the most efficient, in terms of printing time, 3D printers available as part of a distributed manufacturing concept.

D. AREAS FOR FURTHER RESEARCH

This report used Chapter III to show the breadth of AM considerations. This report was only able to cover a portion of manufacturing considerations. Research into any of these requirements would provide valuable insight into the overall manufacturing system.

Other research objectives that would provide value to the military would be:

- the repeatability of printed parts on the same or separate printers
- the effect that part geometry has on manufacturing time

- the effect that part placement and orientation on a build plate has on manufacturing time

Performing a system engineering evaluation of the proper make up of a distributed manufacturing facility would considerably assist the Army in purchasing the correct equipment and staffing combination. One evaluation could be the number of printers that can be supported by one post-processing system. Another evaluation could be the number of printers that a single person can operate.

Other services may have additional consideration and other potential benefits when using AM. Due to the Navy’s remote operations at sea, the expectation is that on-board additive manufacturing capabilities will greatly improve a ship’s readiness. Research into the maximum sea state that a printer is capable of operating while aboard a given class of ship would provide the Navy information of additional equipment required for their unique operational environment.

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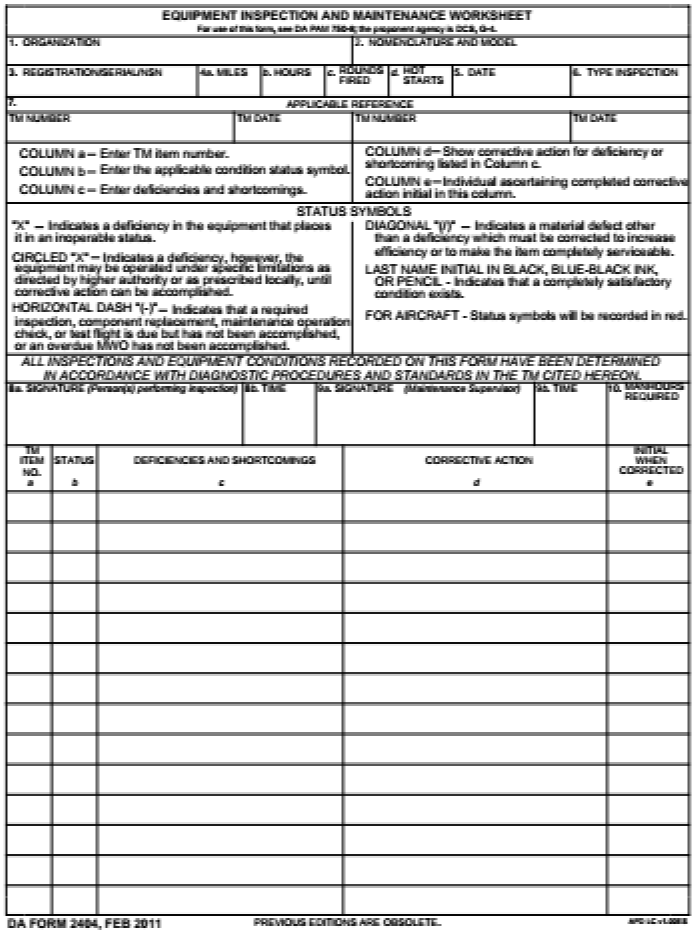
APPENDIX A. DA FORM 2404 – EQUIPMENT INSPECTION AND MAINTENANCE WORKSHEET



EQUIPMENT INSPECTION AND MAINTENANCE WORKSHEET

For use of this form, see DA PAM 750-8; the proponent agency is DCS, G-4.

1. ORGANIZATION
2. NOMENCLATURE AND MODEL
3. REGISTRATION/SERIAL/NSN
4a. MILES
b. HOURS
c. ROUNDS FIRED
d. HOT STARTS
5. DATE
6. TYPE INSPECTION
7. APPLICABLE REFERENCE

TM NUMBER	TM DATE	TM NUMBER	TM DATE

COLUMN a – Enter TM item number.
COLUMN b – Enter the applicable condition status symbol.
COLUMN c – Enter deficiencies and shortcomings.
COLUMN d – Show corrective action for deficiency or shortcoming listed in Column c.
COLUMN e – Individual ascertaining completed corrective action initial in this column.

STATUS SYMBOLS

"X" – Indicates a deficiency in the equipment that places it in an inoperable status.

CIRCLED "X" – Indicates a deficiency, however, the equipment may be operated under specific limitations as directed by higher authority or as prescribed locally, until corrective action can be accomplished.

HORIZONTAL DASH "(-)" – Indicates that a required inspection, component replacement, maintenance operation check, or test flight is due but has not been accomplished, or an overdue MWO has not been accomplished.

DIAGONAL "(/)" – Indicates a material defect other than a deficiency which must be corrected to increase efficiency or to make the item completely serviceable.

LAST NAME INITIAL IN BLACK, BLUE-BLACK INK, OR PENCIL - Indicates that a completely satisfactory condition exists.

FOR AIRCRAFT - Status symbols will be recorded in red.

ALL INSPECTIONS AND EQUIPMENT CONDITIONS RECORDED ON THIS FORM HAVE BEEN DETERMINED IN ACCORDANCE WITH DIAGNOSTIC PROCEDURES AND STANDARDS IN THE TM CITED HEREON.

8a. SIGNATURE (Person(s) performing inspection)	8b. TIME	9a. SIGNATURE (Maintenance Supervisor)	9b. TIME	10. MANHOURS REQUIRED

TM ITEM NO. a	STATUS b	DEFICIENCIES AND SHORTCOMINGS c	CORRECTIVE ACTION d	INITIAL WHEN CORRECTED e

DA FORM 2404, FEB 2011 PREVIOUS EDITIONS ARE OBSOLETE.

The DA Form 2404 is used to record maintenance inspections on Army equipment. This form could be used to authorize the use of additively manufactured repair parts on equipment.

Figure 18. Department of the Army Form 2404. Source: DA (2011).

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APPENDIX B. SOFTWARE TEST CONFIGURATION

Table 8. MakerBot Z72 Replica Software Settings

Part	Claw Holder	Bottom Claw	Top Claw	Both Claws	Flipper Wheel
Print Mode	Balanced	Balanced	Balanced	Balanced	Balanced
Support	Yes	Yes	Yes	Yes	Yes
Infill Density	50%	50%	50%	50%	50%
Layer Height	0.1 mm	0.1 mm	0.1 mm	0.1 mm	0.1 mm
Number of Shells	2	2	2	2	3
Chamber Heater Temperature	40 C	40 C	40 C	40 C	40 C
Travel Speed	150 mm/s	150 mm/s	150 mm/s	150 mm/s	150 mm/s
Extruder Temperature	215 C	215 C	215 C	215 C	215 C
Filament Diameter	1.77 mm	1.77 mm	1.77 mm	1.77 mm	1.77 mm
Retraction Distance	0.875 mm	0.875 mm	0.5 mm	0.875 mm	0.875 mm
Roof Thickness	1.002 mm	1.002 mm	1.002 mm	1.002 mm	1.002 mm
Fix Shell Start	No	No	No	No	No
Shell Print Speed	40 mm/s	40 mm/s	40 mm/s	40 mm/s	40 mm/s
Shell Starting Point	215	215	215	215	215
Infill Layer Height	0.102 mm	0.102 mm	0.102 mm	0.102 mm	0.102 mm
Infill Pattern	Hexagonal	Hexagonal	Hexagonal	Hexagonal	Hexagonal
Infill Print Speed	110 mm/s	110 mm/s	110 mm/s	110 mm/s	110 mm/s
Floor Thickness	1.0 mm	1.0 mm	1.0 mm	1.0 mm	1.0 mm
Support Angle	68	68	68	68	68
Support Density	16%	16%	16%	16%	16%
Support to Model Spacing	0.4 mm	0.4 mm	0.4 mm	0.4 mm	0.4 mm
Support Under Bridges	No	No	No	No	No
First Model Layer Cooling Fan Speed	50%	50%	50%	50%	50%
First Model Layer Speed	50 mm/s	50 mm/s	50 mm/s	50 mm/s	50 mm/s
First Raft Layer Cooling Fan Speed	50%	50%	50%	50%	50%
First Raft layer Speed	10 mm/s	10 mm/s	10 mm/s	10 mm/s	10 mm/s
Raft	Yes	Yes	Yes	Yes	Yes
Raft Size	3 mm	3 mm	3 mm	3 mm	3 mm
Raft to Model Vertical Offset	0.22	0.22	0.22	0.22	0.22

Table 9. Markforge Mark Two Software Settings

Material	Onyx					Carbon Fiber Impregnated Onyx				
Part	Claw Holder	Bottom Claw	Top Claw	Both Claws	Flipper Wheel	Claw Holder	Bottom Claw	Top Claw	Both Claws	Flipper Wheel
Scale	1	1	1	1	1	1	1	1	1	1
Plastic Material	Onyx	Onyx	Onyx	Onyx	Onyx	Onyx	Onyx	Onyx	Onyx	Onyx
Use Fiber	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Fiber Material	---	---	---	---	---	Carbon Fiber	Carbon Fiber	Carbon Fiber	Carbon Fiber	Carbon Fiber
Total Fiber Layers	---	---	---	---	---	144 (max)	114 (max)	114 (max)	114 (max)	119 (max)
Fiber Fill Type	---	---	---	---	---	Isotropic Fiber	Isotropic Fiber	Isotropic Fiber	Isotropic Fiber	Isotropic Fiber
Concentric Fiber Rings	---	---	---	---	---	2	2	2	2	2
Fiber Angles	---	---	---	---	---	0, 45, 90, 135	0, 45, 90, 135	0, 45, 90, 135	0, 45, 90, 135	0, 45, 90, 135
Use Supports	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Turbo Supports (Beta)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Support Angles	0	0	0	0	0	0	0	0	0	0
Raise Part	No	No	No	No	No	No	No	No	No	No
Expand Thin Features	No	No	No	No	No	No	No	No	No	No
Use Brim	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Original Units	Imperial	Imperial	Imperial	Imperial	Metric	Imperial	Imperial	Imperial	Imperial	Metric
Layer Hight (mm)	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
Fill Pattern	Hexagonal Fill	Hexagonal Fill	Hexagonal Fill	Hexagonal Fill	Hexagonal Fill	Hexagonal Fill	Hexagonal Fill	Hexagonal Fill	Hexagonal Fill	Hexagonal Fill
Fill Density	50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Roof and Fiber Layers	4	4	4	4	4	4	4	4	4	4
Wall Layers	2	2	2	2	2	2	2	2	2	2
Description	---	---	---	---	---	---	---	---	---	---

APPENDIX C. TEST DATA

Table 10. Original Test Data

Test No.	Part No.	Part	Printer	Matrial	Estimated Mass (g)	Estimated Time (H:MM)	Prepare Printer (1.5) (H:MM:SS)			Print Time (1.6) (H:MM:SS)			Clear Printer (1.7, 1.8) (H:MM:SS)			Printed Mass (g)	Post Processing Time (1.9) (MM:SS)	Total Time (H:MM:SS)	Comments
							Start	Finish	Ellasped	Start	Finish	Ellasped	Start	Finish	Ellasped				
33	1	Small Flipper Wheel W/ Spacer	Maker Bot	PLA	21.08	3:29	13:47:09	13:52:56	0:05:47	13:52:56	17:07:56	3:15:00	9:18:27	9:18:52	0:00:25	20.2	03:29	3:24:41	
56	2	Small Flipper Wheel W/ Spacer	Maker Bot	PLA	21.08	3:29	13:58:09	14:03:53	0:05:44	14:03:53	17:19:38	3:15:45	8:53:30	8:53:51	0:00:21	20.4	03:12	3:25:02	
48	3	Small Flipper Wheel W/ Spacer	Maker Bot	PLA	21.08	3:29	8:28:42	8:39:50	0:11:08	8:39:50	11:54:57	3:15:07	14:20:47	14:21:14	0:00:27	20.4	04:48	3:31:30	Belive the long warm up time is due to the lab being cooler than normal
35	4	Small Flipper Wheel W/ Spacer	Maker Bot	Tough PLA	22.01	3:31	14:13:26	14:18:00	0:04:34	14:18:00	17:34:30	3:16:30	13:17:41	13:18:04	0:00:23	20.2	11:08	3:32:35	
28	5	Small Flipper Wheel W/ Spacer	Maker Bot	Tough PLA	22.01	3:31	10:47:29	10:55:27	0:07:58	10:55:27	14:11:59	3:16:32	15:31:17	15:31:47	0:00:30	20.1	19:22	3:44:22	
5	6	Small Flipper Wheel W/ Spacer	Maker Bot	Tough PLA	22.01	3:31	9:51:01	9:58:33	0:07:32	9:58:33	13:15:09	3:16:36	13:22:16	13:22:51	0:00:35	19.8	38:28	4:03:11	
53	7	Small Flipper Wheel W/ Spacer	Mark 2	Carbon Fiber	23.57	5:16	16:08:31	16:11:30	0:02:59	16:11:30	20:31:36	4:20:06	8:59:19	8:59:41	0:00:22	18.5	01:26	4:24:53	
14	8	Small Flipper Wheel W/ Spacer	Mark 2	Carbon Fiber	23.57	5:16	17:04:09	17:07:13	0:03:04	17:07:13	21:37:44	4:30:31	17:09:27	17:09:52	0:00:25	18.6	00:48	4:34:48	
55	9	Small Flipper Wheel W/ Spacer	Mark 2	Carbon Fiber	23.57	5:16	9:13:12	9:16:24	0:03:12	9:16:24	13:41:51	4:25:27	9:42:21	9:42:38	0:00:17	18.4	01:17	4:30:13	
59	10	Small Flipper Wheel W/ Spacer	Mark 2	Onxy	13.73	3:11	8:55:41	8:58:42	0:03:01	8:58:42	11:44:03	2:45:21	12:27:43	12:28:02	0:00:19	12.1	00:51	2:49:32	
6	11	Small Flipper Wheel W/ Spacer	Mark 2	Onxy	13.73	3:11	9:30:22	9:33:29	0:03:07	9:33:29	12:18:52	2:45:23	13:04:03	13:04:36	0:00:33	12.1	06:28	2:55:31	Took longer to post-process due to material splater on the side and edge of part
13	12	Small Flipper Wheel W/ Spacer	Mark 2	Onxy	13.73	3:11	10:02:30	10:05:32	0:03:02	10:05:32	12:50:52	2:45:20	17:01:56	17:02:17	0:00:21	12.3	01:17	2:50:00	
30	13	Claw Holder	Maker Bot	PLA	22.23	4:26	8:57:17	9:04:36	0:07:19	9:04:36	13:05:19	4:00:43	13:45:20	13:45:40	0:00:20	25.5	07:20	4:15:42	
47	14	Claw Holder	Maker Bot	PLA	22.26	4:26	14:51:53	14:58:52	0:06:59	14:58:52	18:59:32	4:00:40	8:26:42	8:26:56	0:00:14	26.0	06:26	4:14:19	
50	15	Claw Holder	Maker Bot	PLA	22.26	4:26	14:23:32	14:31:34	0:08:02	14:31:34	18:33:04	4:01:30	8:36:09	8:36:26	0:00:17	25.8	08:09	4:17:58	
19	16	Claw Holder	Maker Bot	Tough PLA	22.60	4:27	9:19:27	9:27:28	0:08:01	9:27:28	13:31:20	4:03:52	15:35:20	15:35:57	0:00:37	24.2	10:58	4:23:28	
27	17	Claw Holder	Maker Bot	Tough PLA	22.93	4:27	14:40:27	14:47:42	0:07:15	14:47:42	18:49:06	4:01:24	10:44:01	10:44:26	0:00:25	24.4	10:26	4:19:30	
43	18	Claw Holder	Maker Bot	Tough PLA	22.93	4:27	8:14:31	8:25:02	0:10:31	8:25:02	12:26:38	4:01:36	14:40:50	14:41:10	0:00:20	24.3	08:26	4:20:53	
36	19	Claw Holder	Mark 2	Carbon Fiber	39.50	8:17	16:51:20	16:54:20	0:03:00	16:54:20	0:33:14	7:38:54	13:30:18	13:30:41	0:00:23	35.2	05:37	7:47:54	
23	20	Claw Holder	Mark 2	Carbon Fiber	39.50	8:17	12:18:18	12:21:11	0:02:53	12:21:11	14:56:54	7:39:09	15:13:56	15:14:24	0:00:28	35.2	05:47	7:48:17	Print stopped due to fiber jam, was able to complete print. Elapse print reflects printing time not down time due to corretive actions
41	21	Claw Holder	Mark 2	Carbon Fiber	39.50	8:17	10:50:29	10:53:41	0:03:12	10:53:41	fail	Fail	fail	fail	fail	fail	fail	fail	Four fiber jams, decided to reprint part
64	21-1	Claw Holder	Mark 2	Carbon Fiber	39.50	8:17	12:29:57	12:32:28	0:02:31	12:32:28	fail	Fail	fail	fail	fail	fail	fail	fail	Massive Failure, See Photos
65	21-2	Claw Holder	Mark 2	Carbon Fiber	39.50	8:17	14:52:40	14:55:15	0:02:35	14:55:15	22:34:04	7:38:49	9:31:49	9:32:05	0:00:16	35.0	07:18	7:48:58	
2	22	Claw Holder	Mark 2	Onxy	15.49	2:45	9:15:55	9:18:55	0:03:00	9:18:55	11:44:41	2:25:46	11:47:21	11:48:00	0:00:39	13.9	03:23	2:32:48	
16	23	Claw Holder	Mark 2	Onxy	15.28	2:45	9:17:32	9:20:39	0:03:07	9:20:39	11:46:24	2:25:45	12:47:58	12:48:29	0:00:31	13.9	02:32	2:31:55	
12	24	Claw Holder	Mark 2	Onxy	15.28	2:45	15:11:57	15:14:59	0:03:02	15:14:59	fail	Fail	fail	fail	fail	fail	fail	fail	Bottom layers were pealing from build plate, reapplyed glue to buid plate
61	24-1	Claw Holder	Mark 2	Onxy	15.28	2:45	15:29:19	15:31:57	0:02:38	15:31:57	17:58:06	2:26:09	10:00:34	10:00:57	0:00:23	14.0	01:00	2:30:10	
34	25	Packbot Top Claw	Maker Bot	PLA	23.60	4:25	9:11:04	9:20:08	0:09:04	9:20:08	13:41:16	4:10:53	13:57:17	13:57:36	0:00:19	25.6	05:58	4:26:14	Ran out of fiber, print stopped. Able to restart print, Elasped print time reflects the actual print time and does not include down time
60	26	Packbot Top Claw	Maker Bot	PLA	23.60	4:25	15:36:48	15:43:29	0:06:41	15:43:29	19:49:54	4:06:25	9:18:29	9:18:42	0:00:13	25.6	05:37	4:18:56	
18	27	Packbot Top Claw	Maker Bot	PLA	23.60	4:25	16:57:09	17:03:03	0:05:54	17:03:03	21:12:52	4:09:49	13:00:00	13:00:23	0:00:23	23.7	fail	fail	Fillement slipage, Due to tangle roll of fillement,meased up the top of the build, Reprinted part

Test No.	Part No.	Part	Printer	Matrial	Estimated Mass (g)	Estimated Time (H:MM)	Prepare Printer (1.5) (H:MM:SS)			Print Time (1.6) (H:MM:SS)			Clear Printer (1.7, 1.8) (H:MM:SS)			Printed Mass (g)	Post Processing Time (1.9) (MM:SS)	Total Time (H:MM:SS)	Comments
							Start	Finish	Ellasped	Start	Finish	Ellasped	Start	Finish	Ellasped				
62	27-1	Packbot Top Claw	Maker Bot	PLA	23.60	4:25	13:08:02	13:16:17	0:08:15	13:16:17	17:22:44	4:06:27	8:52:58	8:53:16	0:00:18	25.8	06:00	4:21:00	
44	28	Packbot Top Claw	Maker Bot	Tough PLA	24.84	4:27	14:43:29	14:51:07	0:07:38	14:51:07	18:58:56	4:07:49	9:12:11	9:12:36	0:00:25	25.2	07:20	4:23:12	
29	29	Packbot Top Claw	Maker Bot	Tough PLA	24.84	4:27	15:34:22	15:40:41	0:06:19	15:40:41	19:48:36	4:07:55	8:39:23	8:39:48	0:00:25	25.1	04:19	4:18:58	
17	30	Packbot Top Claw	Maker Bot	Tough PLA	24.84	4:27	10:38:26	10:46:39	0:08:13	10:46:39	14:54:28	4:07:49	16:39:22	16:39:54	0:00:32	24.0	10:54	4:27:28	
26	31	Packbot Top Claw	Mark 2	Carbon Fiber	28.54	6:11	15:18:47	15:22:57	0:04:10	15:22:57	fail	Fail	fail	fail	fail	fail	fail	fail	Removed Print from build plate, had to reprint part
63	31-1	Packbot Top Claw	Mark 2	Carbon Fiber	28.54	6:11	11:42:59	11:46:08	0:03:09	11:46:08	17:35:46	5:49:38	9:15:21	9:15:45	0:00:24	24.9	04:45	5:57:56	
3	32	Packbot Top Claw	Mark 2	Carbon Fiber	28.54	6:11	11:50:01	11:52:47	0:02:46	11:52:47	17:37:02	5:44:15	9:27:57	9:28:23	0:00:26	24.9	04:34	5:52:01	
1	33	Packbot Top Claw	Mark 2	Carbon Fiber	28.54	6:11	14:30:21	14:33:35	0:03:14	14:33:35	20:17:47	5:44:12	9:02:18	9:02:50	0:00:32	24.9	03:25	5:51:23	
32	34	Packbot Top Claw	Mark 2	Onxy	16.63	3:37	12:47:33	12:50:26	0:02:53	12:50:26	16:07:30	3:17:04	16:49:32	16:49:51	0:00:19	15.1	03:43	3:23:59	
11	35	Packbot Top Claw	Mark 2	Onxy	16.63	3:37	8:24:37	8:27:38	0:03:01	8:27:38	11:50:07	3:22:29	15:10:23	15:10:43	0:00:20	15.1	03:04	3:28:54	
20	36	Packbot Top Claw	Mark 2	Onxy	16.63	3:37	12:50:37	12:53:41	0:03:04	12:53:41	16:10:45	3:17:04	16:11:35	16:11:58	0:00:23	15.1	03:22	3:23:53	
8	37	PackBot Bottom Claw	Maker Bot	PLA	23.58	4:24	9:34:18	9:42:14	0:07:56	9:42:14	13:47:18	4:05:04	15:43:33	15:44:02	0:00:29	25.3	07:31	4:21:00	
46	38	PackBot Bottom Claw	Maker Bot	PLA	23.58	4:24	9:31:14	9:39:49	0:08:35	9:39:49	13:45:50	4:06:01	14:49:50	14:50:12	0:00:22	25.4	06:49	4:21:47	
25	39	PackBot Bottom Claw	Maker Bot	PLA	23.58	4:24	8:21:18	8:30:27	0:09:09	8:30:27	12:37:08	4:06:41	14:23:02	14:23:24	0:00:22	25.3	05:48	4:22:00	
52	40	PackBot Bottom Claw	Maker Bot	Tough PLA	24.80	4:25	8:50:39	9:00:44	0:10:05	9:00:44	13:07:35	4:06:51	13:43:53	13:44:14	0:00:21	25.2	08:22	4:25:39	
4	41	PackBot Bottom Claw	Maker Bot	Tough PLA	23.04	2:25	15:00:08	15:03:35	0:03:27	15:03:35	17:17:09	2:13:34	9:32:05	9:32:37	0:00:32	21.4	05:41	2:23:14	
57	42	PackBot Bottom Claw	Maker Bot	Tough PLA	24.80	4:25	9:13:44	9:23:04	0:09:20	9:23:04	13:29:47	4:06:43	15:27:08	15:27:25	0:00:17	25.3	41:32	4:57:52	Shifted on Raft, destroyed durring post processing
67	42-1	PackBot Bottom Claw	Maker Bot	Tough PLA	24.80	4:25			0:07:04			4:06:19			0:00:20	25.2	05:29		
51	43	PackBot Bottom Claw	Mark 2	Carbon Fiber	28.52	6:10	8:54:20	8:57:26	0:03:06	8:57:26	14:45:56	5:48:30	16:06:28	16:06:50	0:00:22	24.9	04:20	5:56:18	
9	44	PackBot Bottom Claw	Mark 2	Carbon Fiber	28.52	6:10	13:07:09	13:10:07	0:02:58	13:10:07	18:53:11	5:43:04	8:19:00	8:19:25	0:00:25	25.0	05:13	5:51:40	
45	45	PackBot Bottom Claw	Mark 2	Carbon Fiber	28.52	6:10	8:32:44	8:35:48	0:03:04	8:35:48	14:24:18	5:48:30	14:24:50	14:25:14	0:00:24	24.8	04:07	5:56:05	
49	46	PackBot Bottom Claw	Mark 2	Onxy	16.45	3:31	14:27:27	14:29:49	0:02:22	14:29:49	17:40:46	3:10:57	8:53:02	8:53:19	0:00:17	14.9	02:50	3:16:26	
22	47	PackBot Bottom Claw	Mark 2	Onxy	16.45	3:31	8:12:52	8:15:56	0:03:04	8:15:56	11:32:13	3:16:17	12:16:11	12:16:32	0:00:21	14.9	03:22	3:23:04	
31	48	PackBot Bottom Claw	Mark 2	Onxy	16.45	3:31	9:17:48	9:20:45	0:02:57	9:20:45	12:37:08	3:16:23	12:43:09	12:43:33	0:00:24	15.0	04:04	3:23:48	
10	49	Top & Bottom Claw	Maker Bot	PLA	47.45	8:55	15:49:26	16:00:30	0:11:04	16:00:30	0:16:13	8:15:43	10:13:52	10:14:33	0:00:41	51.3	09:42	8:37:10	
24	50	Top & Bottom Claw	Maker Bot	PLA	47.54	8:55	15:55:02	16:01:17	0:06:15	16:01:17	0:17:06	8:15:49	10:29:17	10:29:42	0:00:25	51.5	12:47	8:35:16	
38	51	Top & Bottom Claw	Maker Bot	PLA	47.54	8:55	13:35:41	13:43:32	0:07:51	13:43:32	22:01:47	8:18:15	10:34:43	10:35:08	0:00:25	51.2	11:17	8:37:48	
7	52	Top & Bottom Claw	Maker Bot	Tough PLA	49.70	8:57	13:28:12	13:32:54	0:04:42	13:32:54	21:50:37	8:17:43	8:26:31	8:27:05	0:00:34	49.0	18:29	8:41:28	
39	53	Top & Bottom Claw	Maker Bot	Tough PLA	49.70	8:57	10:49:59	10:57:56	0:07:57	10:57:56	19:16:19	8:18:23	9:14:24	9:14:51	0:00:27	49.8	09:51	8:36:38	
40	54	Top & Bottom Claw	Maker Bot	Tough PLA	49.70	8:57	9:16:01	9:25:23	0:09:22	9:25:23	17:43:42	8:18:19	8:12:00	8:12:29	0:00:29	49.8	13:13	8:41:23	
58	55	Top & Bottom Claw	Mark 2	Carbon Fiber	57.07	12:19	9:44:11	9:47:23	0:03:12	9:47:23	20:51:40	11:04:17	8:54:45	8:55:06	0:00:21	43.5	04:19	11:12:09	
54	56	Top & Bottom Claw	Mark 2	Carbon Fiber	57.07	12:19	9:15:39	9:18:40	0:03:01	9:18:40	22:50:40	11:07:05	9:10:39	9:11:04	0:00:25	49.9	07:24	11:17:55	Fiber jam able to continue print Elasp print time is total print time with out down time
21	57	Top & Bottom Claw	Mark 2	Carbon Fiber	57.07	12:19	16:13:51	16:16:08	0:02:17	16:16:08	3:15:05	10:58:57	10:24:11	10:24:45	0:00:34	50.0	09:12	11:11:00	
42	58	Top & Bottom Claw	Mark 2	Onxy	33.16	7:05	9:33:00	9:36:00	0:03:00	9:36:00	fail	fail	fail	fail	fail	fail	fail	fail	Pulled part from build plate. Replaced build plate
66	58-1	Top & Bottom Claw	Mark 2	Onxy	33.16	7:05	15:09:25	15:12:14	0:02:49	15:12:14	21:38:09	6:25:55	8:31:14	8:31:44	0:00:30	29.9	04:55	6:34:09	
15	59	Top & Bottom Claw	Mark 2	Onxy	33.16	7:05	13:12:13	13:15:13	0:03:00	13:15:13	19:46:37	6:31:24	9:07:33	9:08:02	0:00:29	30.2	04:30	6:39:23	
37	60	Top & Bottom Claw	Mark 2	Onxy	33.16	7:05	13:39:55	13:43:17	0:03:22	13:43:17	20:40:02	6:33:50	10:40:24	10:40:42	0:00:18	30.2	06:46	6:44:16	Printer thought it was out of fiber. Over rode low fiber meter and restarted print

This table contains data as recorded by the lab tech that has been rearranged by part number, grouping the data by part. The red line highlight the failed parts while the yellow lines highlight the parts that paused during printing but the part was recoverable.

Table 11. Filament Changes for the MakerBot Z71 Replicator

Starting Material	Final Material	Ending Part	Starting Part	Filament Change (H:MM:SS)		
				Start	Finish	Elapsed
Tough PLA	PLA	52	37	8:44:35	8:54:04	0:09:29
PLA	Tough PLA	49	30	10:14:33	10:32:36	0:18:03
Tough PLA	PLA	30	27	16:39:54	16:54:24	0:14:30
PLA	Tough PLA	27-1	16	8:56:12	9:09:06	0:12:54
Tough PLA	PLA	16	50	15:38:25	15:51:49	0:13:24
PLA	Tough PLA	39	17	14:26:36	14:40:06	0:13:30
Tough PLA	PLA	29	13	9:41:42	9:56:09	0:14:27
PLA	Tough PLA	25	4	14:01:08	14:12:58	0:11:50
Tough PLA	PLA	4	51	13:20:20	13:32:07	0:11:47
PLA	Tough PLA	51	53	10:36:49	10:49:23	0:12:34
Tough PLA	PLA	28	38	9:15:36	9:30:05	0:14:29
PLA	Tough PLA	15	40	8:37:13	8:49:34	0:12:21
Tough PLA	PLA	40	2	13:46:24	13:57:49	0:11:25
PLA	Tough PLA	2	42	8:55:16	9:09:00	0:13:44
Tough PLA	PLA	42	26	15:23:58	15:35:44	0:11:46

Table 12. Manufacturing Time by Part

Part	Part Time Avg. (h:mm:ss)						Part Mass Avg. (g)				Time per gram			
	Estimated	Prepare	Print	Clear Printer	Post Processing	Total	Estimated	Printed	Finished	Removed Mass	Estimated	Printed	Post Processing/ Removed Mass	Total/ Finished
Small Flipper Wheel W/ Spacer	3:51:45	0:05:06	3:25:38	0:00:25	0:07:43	3:38:52	20.10	17.76	15.08	2.68	0:11:42	0:11:35	0:03:26	0:14:31
Claw Holder	4:58:45	0:05:27	4:32:01	0:00:24	0:06:27	4:44:19	24.98	24.78	22.36	2.43	0:11:45	0:10:59	0:03:16	0:12:27
Packbot Top Claw	4:40:00	0:05:21	4:20:10	0:00:23	0:05:15	4:31:10	23.40	22.61	18.31	4.30	0:12:00	0:11:30	0:01:26	0:14:50
PackBot Bottom Claw	4:27:30	0:05:19	4:09:01	0:00:23	0:05:18	4:20:01	23.23	22.36	18.37	3.99	0:11:33	0:11:08	0:01:31	0:14:11
Top & Bottom Claw	9:19:00	0:05:24	8:32:08	0:00:28	0:09:22	8:47:23	46.86	44.69	35.78	8.92	0:11:57	0:11:28	0:01:12	0:14:46
Half time for Top & Bottom Claw	4:39:30	0:02:42	4:16:04	0:00:14	0:04:41	4:23:41	23.43	22.35	17.89	4.46	---	---	---	---

Part	Percent of Total Manufacturing Time						Additional Manufacturing Time
	Estimated	Prepare	Print	Clear Printer	Post Processing	Total	
Small Flipper Wheel W/ Spacer	105.89%	2.33%	93.96%	0.19%	3.52%	100.00%	6.04%
Claw Holder	105.07%	1.91%	95.67%	0.14%	2.27%	100.00%	4.33%
Packbot Top Claw	103.26%	1.98%	95.95%	0.14%	1.94%	100.00%	4.05%
PackBot Bottom Claw	102.88%	2.04%	95.77%	0.15%	2.04%	100.00%	4.23%
Top & Bottom Claw	106.00%	1.02%	97.11%	0.09%	1.78%	100.00%	2.89%
Half time for Top & Bottom Claw	106.00%	1.02%	97.11%	0.09%	1.78%	100.00%	2.89%
Average percent of time	104.85%	1.72%	95.93%	0.13%	2.22%	100.00%	4.07%
max	106.00%	2.33%	97.11%	0.19%	3.52%	100.00%	2.89%
Min	102.88%	1.02%	93.96%	0.09%	1.78%	100.00%	6.04%
StDev	1.43%	0.56%	1.16%	0.04%	0.67%	0.00%	1.16%

This table presents the average times to perform the identified manufacturing task demonstrated during testing. This table averages the raw time of manufacturing as well as normalizes the time per gram printed. Finally, the bottom section of the table represents the time as a percentage of total manufacturing time.

Table 13. Manufacturing Time by Printer and Material

Printer	Material	Part Time Avg. (h:mm:ss)						Part Mass Avg. (g)				Time per gram			
		Estimated	Prepare	Print	Clean	Post Processing	Total	Estimated	Printed	Finished	Removed Mass	Estimated	Printed	Post processing/ Removed Mass	Total/ Finished
Maker Bot	PLA	5:07:48	0:07:59	4:45:20	0:00:23	0:07:00	5:00:42	27.60	29.69	22.65	7.03	0:11:07	0:09:36	0:01:05	0:13:14
Maker Bot	Tough PLA	5:01:24	0:07:23	4:38:45	0:00:28	0:12:10	4:58:45	28.75	28.58	21.68	6.90	0:10:25	0:09:41	0:02:06	0:13:43
Mark 2	Carbon Fiber	7:38:36	0:02:58	6:56:06	0:00:24	0:04:38	7:04:06	35.44	30.25	28.18	2.07	0:12:59	0:13:49	0:02:42	0:15:06
Mark 2	Onyx	4:01:48	0:02:58	3:39:00	0:00:24	0:03:28	3:45:51	19.06	17.25	15.40	1.85	0:12:40	0:12:39	0:02:47	0:14:32

Printer	Material	Percent of Total Manufactuing Time						Additional Manufacturing Time
		Estimated	Prepare	Print	Clean	Post Processing	Total	
Maker Bot	PLA	102.36%	2.66%	94.89%	0.12%	2.33%	100.00%	5.11%
Maker Bot	Tough PLA	100.89%	2.47%	93.31%	0.15%	4.07%	100.00%	6.69%
Mark 2	Carbon Fiber	108.13%	0.70%	98.11%	0.10%	1.09%	100.00%	1.89%
Mark 2	Onyx	107.06%	1.31%	96.97%	0.18%	1.54%	100.00%	3.03%
Avg		104.61%	1.78%	95.82%	0.14%	2.26%	100.00%	4.18%
Max		108.13%	2.66%	98.11%	0.18%	4.07%	100.00%	1.89%
Min		100.89%	0.70%	93.31%	0.10%	1.09%	100.00%	6.69%
StDev		3.53%	0.94%	2.14%	0.04%	1.31%	0.00%	2.14%

This table presents the average times to perform the identified manufacturing task demonstrated during testing. This table averages the raw time of manufacturing as well as normalizes the time per gram printed. Finally, the bottom section of the table represents the time as a percentage of total manufacturing time.

Table 14. Estimated Versus Actual Print by Part, Software and Material

Part	**Software**	**Material**	**Avg. Printing Time**		**Difference**	**% Over Estimate**
			Estimated	**Actual (Avg.)**		
Small Flipper Wheel W/ Spacer	MakerBot Printer	PLA	3:29:00	3:15:17	0:13:43	7.02%
Small Flipper Wheel W/ Spacer	MakerBot Printer	Tough PLA	3:31:00	3:16:33	0:14:27	7.35%
Small Flipper Wheel W/ Spacer	Eiger	Carbon Fiber	5:16:00	4:25:21	0:50:39	19.09%
Small Flipper Wheel W/ Spacer	Eiger	Onxy	3:11:00	2:45:21	0:25:39	15.51%
Claw Holder	MakerBot Printer	PLA	4:26:00	4:00:58	0:25:02	10.39%
Claw Holder	MakerBot Printer	Tough PLA	4:27:00	4:02:17	0:24:43	10.20%
Claw Holder	Eiger	Carbon Fiber	8:17:00	5:59:26	2:17:34	38.27%
Claw Holder	Eiger	Onxy	2:45:00	2:25:53	0:19:07	13.10%
Packbot Top Claw	MakerBot Printer	PLA	4:25:00	4:08:24	0:16:37	6.69%
Packbot Top Claw	MakerBot Printer	Tough PLA	4:27:00	4:07:51	0:19:09	7.73%
Packbot Top Claw	Eiger	Carbon Fiber	6:11:00	5:46:02	0:24:58	7.22%
Packbot Top Claw	Eiger	Onxy	3:37:00	3:18:52	0:18:08	9.12%
PackBot Bottom Claw	MakerBot Printer	PLA	4:24:00	4:05:55	0:18:05	7.35%
PackBot Bottom Claw	MakerBot Printer	Tough PLA	3:55:00	3:38:22	0:16:38	7.62%
PackBot Bottom Claw	Eiger	Carbon Fiber	6:10:00	5:46:41	0:23:19	6.72%
PackBot Bottom Claw	Eiger	Onxy	3:31:00	3:14:32	0:16:28	8.46%
Top & Bottom Claw	MakerBot Printer	PLA	8:55:00	8:16:36	0:38:24	7.73%
Top & Bottom Claw	MakerBot Printer	Tough PLA	8:57:00	8:18:08	0:38:52	7.80%
Top & Bottom Claw	Eiger	Carbon Fiber	12:19:00	11:03:26	1:15:34	11.39%
Top & Bottom Claw	Eiger	Onxy	7:05:00	6:30:23	0:34:37	8.87%

This table presents the average estimated print time that the given software predicts. It compares this time to actual print time average. Note the resulting percentage is the amount the software over estimates the print time not the manufacturing time.

APPENDIX D. TEST PHOTOGRAPHS

This appendix shows examples of parts that printed with defects requiring the part to be reprinted or adding time to the post processing.

This is the result of attempting to print part 21-1. This was the second attempt at printing this part, a claw holder printed with carbon fiber impregnated Onyx on the Mark Two printer. The print began well. However, when the lab tech returned to the lab, he noticed the part was pulled from the build plate and the long thin piece was attached to the filament nozzle, moving with nozzle.

Figure 19. Failed Part 21-1

Part 42, PackBot bottom claw printed with tough PLA on a MakerBot printer. This part printed off-center of the raft. This led to the part being destroyed during post processing.

Figure 20. Failed Part 42

Resulting damage caused during post processing of part 42. Part 42 was printed off center of the raft making the raft difficult to remove from the part, resulting in exposing the internal structure of the part 42.

Figure 21. Bottom View of Damaged Part 42

Material splatter on the edge of a part printed with carbon fiber impregnated Onyx.

Figure 22. Part with Material Splatter

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