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Cost Analysis for 3D Printed Counter-Unmanned Aerial System (C-UAS) Guided Rocket Prototype

December 2024

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Prepared for the Naval Postgraduate School, Monterey, CA 93943.

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ABSTRACT

Low-cost drone use has become prolific in the ongoing conflicts in Ukraine and in the Red Sea. The growing usage of inexpensive unmanned aerial systems (UAS) in military engagements exposes a critical vulnerability of the United States. The United States largely relies on expensive and sophisticated ordnance that have long production lead times. Stockpiles of these munitions are limited and depleting inventories to counter cheaply made threats is unsustainable and creates risks for future military operations. A potential solution is for the United States to develop its own low-cost rockets that are capable of successfully engaging and downing UAS. USINDOPACOM is currently working on a viable prototype that leverages off-the-shelf parts and 3D-printed components that could pave the path for viable alternatives. However, understanding the rocket's cost once it can accomplish the desired outcomes is required. This research aims to provide relevant cost information for USINDOPACOM's prototype rocket with the larger intention of supporting informed strategic decisions for adoption and production of rockets that address the threat created by low-cost UAS. Using both single-variable and multivariable regression analyses, we examine how two key factors—labor hours and range—influence the overall cost of these defense systems. Our study strongly supports selecting the multiple regression model to estimate the prototype's cost.

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LIST OF ACRONYMS AND ABBREVIATIONS

CAD	Computer Aided Design
CADE	Cost Assessment Data Enterprise
CEA	Cost Effectiveness Analysis
COEA	Cost and Operational Effectiveness Analysis
COTS	Commercial Off-the-Shelf
c-UAS	counter-Unmanned Aerial System
DoD	Department of Defense
DPRK	Democratic People's Republic of Korea
FMF	Foreign Military Financing
MODAFL	Ministry of Defense and Armed Forces Logistics
MOU	Memorandum of Understanding
NDAA	National Defense Authorization Act
OLS	Ordinary Least Squares
PDA	Presidential Drawdown Authority
PEO IWS	Program Executive Office Integrated Warfare Systems
PLA	People's Liberation Army
PRC	People's Republic of China
QME	Qualitative Military Edge
SECDEF	Secretary of Defense
SRM	Solid Rocket Motor
THAAD	Terminal High-Altitude Area Defense
TTP	Tactics, Techniques, and Procedures
UAS	Unmanned Aerial System
USD	United States Dollars

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I. INTRODUCTION

A. PROBLEM STATEMENT

The current war in Ukraine and the growing conflicts between Israel and regional Iranian proxies demonstrate how readily available technology can be leveraged to create inexpensive and effective threats in military engagements. Specifically, cheaply made drones and other unmanned aerial systems (UAS) are relatively quick and easy to produce and countering them is rapidly depleting expensive ordnance (Pilkington, 2023). It is unsustainable to continue to expend high-cost munitions to counter low-cost drone threats. For U.S. warships at sea there is a finite storage capacity for munitions, and vessels lack the ability to rearm underway. This problem is compounded by limited national inventories.

The American military industrial complex is currently structured to produce high-quality and high-cost munitions. Due to a mix of acquisition and production decisions, missiles have long lead times, and manufacturers struggle to rapidly replenish stock. For decades the U.S. has been producing weapons intended to overmatch an adversary's arsenal. However, the increasing availability of low-cost technology that can saturate the battle space could prove a viable challenge to this strategic formula. Even if the low-cost drones are less effective, the technology can be used en masse to dwindle our inventory of munition, disrupt the battle space, and produce kinetic effects.

Currently, U.S. missiles have extensive production lead times which impairs the ability to replenish expended stock. It takes roughly five years to produce a surface ship missile (Gueye, 2023, p. xix). This problem has been exacerbated by ongoing military support to Ukraine and Israel. Additional challenges are created by the Department of Defense (DoD) current acquisition framework which makes it very challenging for the DoD to rapidly innovate to response to emerging threats. At this time the U.S. is not outfitted to efficiently counter the high-volume threat that cheap drone technology could pose in a military conflict (Seligman & Berg, 2023).

Houthi launched drones in the Red Sea highlight the threat low-cost UAS poses to U.S. warships. U.S. destroyers have used ordnance that cost an estimated $2.1 million per missile to counter drones that cost as little as $2,000 to produce (Seligman & Berg, 2023; Pilkington, 2023). This asymmetric weapon exchange indicates a critical vulnerability that could put both mission and forces at risk in a protracted conflict especially one that tests naval endurance at sea.

In sum, the United States urgently needs to find viable alternatives to high-cost, low-production-rate munitions to address the price disparity and proliferation of inexpensive UAS (Tucker, 2024).

To address these challenges, the Department of Defense (DoD) has been working to increase ordnance production. The Navy has increased weapons spending 70% from FY2022 to FY2024 (Eckstein, 2024). However, production continues to be constrained by the small pool of solid rocket motors suppliers, long lead times for critical components, and destructive testing methods (Gueye, 2023, p. 1). Despite the increase in multi-year contracts, industry executives admit it will take time for the industrial base to be built up enough to support increased production rates (Eckstein, 2024). Still, this increase in production is focused on producing more of the current high-cost munitions. A gap will still exist in the production of munitions that are cost-effective in countering low-cost threats.

One potential solution to closing this gap may be USINDOPACOM J85's rocket prototype. The rocket is still in the initial stages of develop but it is designed using additive manufacturing and commercially available parts which could allow for cheaper production possibilities and flexibility in fabrication options. Additionally, this alternative method of weapons production could enable scalable and disaggregated manufacturing. Most importantly, creating a low-cost weapon that is effective in countering low-cost UAS could help preserve the inventory of higher cost ordnance for more sophisticated threats.

However, to understand if the prototype offers any cost and time saving advantages over current munitions in the DoD's inventory a rigorous cost estimate is needed. Data is limited on the prototype rocket since it is in its infancy stages of development. As a result, this paper will approach the rocket's potential through an innovative framework approach. It will examine how low-cost drones are redefining modern warfare by analyzing their use in the ongoing conflicts in Ukraine and Israel. Additionally, it will examine the emerging threat drone technology may pose if China tries to invade Taiwan. The research will also look at how the United States is currently trying to handle sluggish munition production rates and efforts to speed up the DoD acquisition process to allow for rapid development of technologies to counter emerging drone threats. An examination of other industries that use 3D printing is required to understand how additive manufacturing technology could be used to reduce manufacturing timelines, production costs, and resupply challenges for defensive missiles. The study includes a limited cost regression based on the development team's stated aspirational rocket range, and it will be used to determine if the rocket prototype could be a suitable alternative to the missiles currently being used to counter UAS threats. The overall goal of the research is to evaluate a potential solution to the threats posed by low-cost drones and inform strategic decisions about USINDOPACOM's 3D printed rocket project.

B. RESEARCH QUESTIONS

1. How much does it cost to build military-capable 2.75-inch class rockets using 100% commercially available off-the-shelf materials?
2. How are drones currently changing warfare?
3. How is additive manufacturing being leveraged in military grade weapons production?
4. What can/should the U.S. do to support the development of these types of systems to its defense partners?

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II. BACKGROUND

A. LITERATURE REVIEW

1. Current DoD Rocket Industry

Two previous Naval Postgraduate School (NPS) theses have looked at possible ways to increase the production rate of naval missiles. These studies specifically analyzed the impact the supply of solid rocket motors had on overall Navy standard missiles production. Gueye (2023) examined ways Program Executive Office Integrated Warfare Systems 3.0 (PEO IWS 3.0) could field and produce surface to air missiles for naval vessels faster. The research looked at SpaceX production processes and current primary contractors' methods to understand the causes of production bottlenecks and identify pathways to increase the rate of production. The research shows that it currently takes roughly five years to produce a single solid rocket motor (SRM).

The problem stems from having a small pool of suppliers, long lead time for critical components, and destructive testing methods (Gueye, 2023, p. 8). Using ExtendSim, Gueye was able to simulate the SRM production process to calculate that the process takes 352 weeks. Gueye experimented with decreasing fabrication activities applying data provided by Aerojet Rocketdyne. Simulations showed that despite reducing each fabrication activity by 30–90% production times only decreased by 18.4% to 290 weeks (Gueye, 2023, p. 57). Gueye was able to determine that order forging, case manufacturing, and case preparation impacted fabrication timelines the most. This research highlights the limitations of increasing production through process reforms and provides a compelling reason to explore new technologies like 3D printing to increase production capacity.

Gureck's (2023) research was based on interviews with commercial and defense rocket manufacturers. His focus was to understand what drives long lead times and to evaluate if commercial space industries could produce military grade missiles faster. Gureck provided a detailed explanation of how China is planning to exploit the US's reliance on expensive weapons and highlights the possibility that China could adopt a saturation tactic using swarms of low-cost drones to assist in this strategy (Gureck, 2023,

p. 9). His research further shows that it will take at least five years with current production levels to build back the munitions inventory that was transferred to support Ukraine (Gureck, 2023, p. 14). Gureck's (2023) research frames the dire consequences of insufficient munitions inventory. He provides compelling evidence that current munitions levels would likely be depleted within weeks if not days if a conflict occurred with China. The research reenforces the need for a rapid increase in missile production capability and urges the DoD to adopt innovative solutions and reconsider risk calculations in new weapons designs to capitalize on emerging technologies (Gureck, 2023, p. 73).

2. Some Background on Innovation Research

Clayton Christensen's *The Innovator's Dilemma* (2024) provides a compelling framework to understand the impact of disruptive technologies on firms at the top of their industries. Disruptive technologies are often innovations that are often worse in product performance in the short term but in the long term bring to market a different value proposition and upend existing markets. Often these technologies are simpler, cheaper, smaller, and more convenient (Christensen, 2024, p. 8). He argues that firms at the top often fail to invest adequately in disruptive technologies, opting instead to invest heavily in the 'best' products until it is too late (Christensen, 2024, p. 5).

This framework can easily be applied to the U.S. military's current weapons dominance. Low-cost drones could very well be a disruptive technology. The U.S. needs to adequately invest to capitalize on this technology now to prevent itself becoming the victim of disruption and losing its position to a rival.

Christian Brose's *The Kill Chain* (2020) picks up many of Christensen's themes and warns of America's deteriorating military advantage in the face emerging technologies and near peer adversaries like China and Russia. Brose urges Congress and senior DoD officials to forge better relationships with Silicon Valley to effectively concentrate investment in key emerging technologies like artificial intelligence and unmanned systems which will be essential for the U.S. military to remain competitive in the future (Brose, 2020, p. 240). Brose also argues that the DoD needs to stop funneling billions of dollars into contracts for legacy military systems and traditional industrial base companies.

Instead, he encourages the DoD to create incentives for innovative firms to work on military problems (Brose, 2020, p. 242).

3. Cost Analysis Techniques

Mislick and Nussbaum's *Cost Estimation* (2015) text provides alternative comprehensive frameworks for costing production, including single and multivariable regression analysis to evaluate cost drivers in defense systems like counter-Unmanned Aerial System (c-UAS) rockets. While single-variable analysis using metrics like weight or range can provide initial cost insights, Mislick and Nussbaum (2015) argue that incorporating multiple technical parameters in cost models allows analysts to develop more accurate predictions compared to using just one explanatory variable (Mislick & Nussbaum, 2015, p. 152). The research emphasizes maintaining statistical relationships between correlated variables to avoid unstable predictions that could misguide acquisition decisions for new c-UAS capabilities.

Mislick and Nussbaum's (2015) analytical techniques provided the framework we use in this thesis to assess cost-capability tradeoffs and support decisions between high-performance custom designs versus leveraging commercial off-the-shelf rocket technologies with modifications for the c-UAS mission.

B. UKRAINE

Drone usage in the war in Ukraine is changing warfare (Kharuk, 2024). On February 24, 2022, Russia invaded Ukraine. Since the invasion Russia has maintained a numerical advantage over Ukraine in manpower, munitions, and military equipment (Bertrand & Lillis, 2024). Ukraine is currently relying heavily on foreign military assistance and leveraging technological innovations to challenge Russian advances. The U.S. has provided over $64.1 billion in military assistance to Ukraine to support their efforts to expel Russian forces and maintain air defense (U.S. Department of State, 2024b; Lopez, 2024a). As of September 6, 2024, the United States has used Presidential Drawdown Authority (PDA) to provide Ukraine with $31.2 billion worth of military stockpile, including munitions (U.S. Department of State, 2024a). PDA allows the president to direct drawdown of stocked U.S. defense articles for faster delivery of foreign aid but dipping into critical military stock creates future risks for U.S. forces.

Multiple (c-UAS) have been provided to Ukraine including VAMPIRE systems, c-UAS gun trucks, mobile c-UAS laser-guided rocket systems, other c-UAS, and ammunition (U.S. Department of State, 2024b). Furthermore, the United States has provided numerous air defense systems including Patriot batteries, more than 20,000 Hydra-70 aircraft rockets, HAWK air defense systems, Stinger anti-aircraft missiles, NASAMS missile systems, and Avenger air defense systems (Lopez, 2024a; U.S. Department of State, 2024b). Stinger missiles have been vital for Ukraine and have been used to down Russian helicopters and even Shahed drones (Hambling, 2024a). However, manufacturers in the U.S. are struggling to produce enough of these systems to keep up with battlefield demand. At the outbreak of the war in Ukraine, the DoD had not purchased Stingers in 18 years (McCleary, 2022). In 2022 the Raytheon CEO told investors that a ramp up in production to support the war effort would be delayed until 2023 due to limited parts and materials. The production facilities also face capacity constraints. The CEO warned that resupplying the global inventory would require a major investment from the U.S. government (McCleary, 2022).

Even with the support of the United States and nearly 50 other partner nations Ukraine has had to create innovative ways to address munition shortfalls and maintain air defense. To do so Ukraine is leveraging drones that are cheaply made and quickly produced (Coles & Sivorka, 2024). Ukraine has stood up the Unmanned Systems Forces, a new armed forces branch dedicated to drone warfare (Kakissis & Harbage, 2024). In 2024 the Ukrainian government dedicated $2 billion to produce over a million first person-view (FPV) drones. To date they have contracted 1.5 million drones and now have the domestic capacity to produce 4 million drones a year (Kakissis & Harbage, 2024).

Since the beginning of the war over 200 Ukrainian companies have been formed to support in the domestic production of drones. Companies like Wild Hornet have created small UAS capable of hitting military targets that cost as little as $700 per unit. This makes drones a cheap alternative to artillery and missiles (Coles & Sivorka, 2024). Additionally, Ukraine is using additive manufacturing or 3D printing to make anti-personnel gravity bombs known as “candy bombs.” The candy bomb casings are being made on a machine that costs $1,200. The bomb’s nose cone, body, and tail are all 3D printed for as little as $3.85 per unit (Baker, 2023). Some producers can make 1,000 800-gram anti-personnel bomb casings a week using this very inexpensive equipment (Baker, 2023).

Candy bombs are often dropped from drones. Explosive payloads as large as 11 pounds have been delivered by drones to attack Russian infantry in the Donetsk region (Baker, 2023). Ukrainian made drones and bombs are becoming increasingly sophisticated and have successfully been used in anti-tank and anti-personnel operations, to drop mines, deliver supplies, and intercept Russian reconnaissance drones (Coles & Sivorka, 2024). Figure 1 shows the 3D printed plastic bomb casings made by Ukrainian firm Steel Hornet.

Figure 1. 3D Printed Munitions Made by Steel Hornet. Source: Hambling (2024c).

The Ukrainian navy has also used drones at sea against Russian warships in the Black Sea (Kakissis & Harbage, 2024). Since the beginning of the war Ukraine has successfully damaged or sunk about 24 Russian vessels using explosive sea drones (Marson, 2024). These drones helped push the Russian Black Sea Fleet away from Sevastopol and enabled critical exports from the port of Odesa (Marson, 2024). Sea drones, like conventional drones, are reshaping warfare. They can be inexpensive to manufacture and can commodify the maritime domain that has been traditionally dominated by manned combat vessels (Marson, 2024).

One of Russia's strategies to win the war in Ukraine is to outlast the supply of U.S. provided munitions (Hambling, 2024a). As an established military power, Russia entered the war with an arsenal of conventional missiles and the largest stockpile of nuclear weapons in the world. Since the beginning of the war Russia has launched over 43,000 missiles and bombs at Ukraine to attack strategic target and stress Ukrainian air defense capabilities (Zelenskyy, 2024). Russia has a wide variety of domestically produced drones, and it is also known to receive military aid from the Democratic People’s Republic of Korea (DPRK), Iran, and the People’s Republic of China (PRC). Domestically, Russia is known to produce the Forpost, a replica of Israel’s IAI Searcher. It also produces Orlan-10s. However, as of October 2024 these are thought to have largely become obsolete in the conflict due to effective Ukrainian counter measures (Kharuk, 2024). Russia has largely replaced the Orlans with SuperCam and ZALA drones. ZALAs are Kamikaze style drones which have an estimated range of 31 to 43 miles. It is speculated that 15–20% of Russian drones are SuperCam S350s (Kharuk, 2024).

In June 2024 Russia and North Korea signed a mutual military assistance pact (Arhirova, 2024). However, prior to this formal agreement the Defense Intelligence Agency confirmed that Russia has used ballistic missiles produced in North Korea as far back as December 30, 2023 (Defense Intelligence Agency, 2024). Hwasong-11 are cheaply made North Korean short-range missiles capable of traveling 435 miles. It is believed that North Korea is getting around sanctions to buy components for its missiles by establishing fake companies in other Asian countries (Mackenzie, 2024). Computer chips that are used in washing machines, phones and cars are purchased and sent into North Korea through China. Experts are concerned that North Korea fueled by oil from Russia could become a major weapons supplier for the China-Russia-Iran bloc (Mackenzie, 2024).

Like North Korea, military cooperation between Russia and Iran has increased. Iran has supported Russia since the beginning of the invasion. Iran has provided Russia with Fath 360s which are close range ballistic missiles with a range of around 75 miles and Shahed-131/136s which are one way attack drones with an estimated cost of $30,000 per unit (Hambling, 2024b; Lopez, 2024a). These inexpensive missiles and drones enable Russia to reserve more sophisticated and expensive long-range missiles for other purposes (Lopez, 2024a). Russia has ramped up its capability to domestically produce Shaed-136s. Iran and Russia’s Ministry of Defense and Armed Forces Logistics (MODAFL) have worked together to produce and finance Iranian-designed drones in Russia (U.S Department of the Treasury, 2024a). The Russian firm, Joint Stock Company Special Economic Zone of Industrial Production Alabuga (SEZ Alabuga) has a contract with the Russian military to assemble UAS from Iran while simultaneously increasingly domestics production of Iranian-designed drones (U.S Department of the Treasury, 2024a). It is estimated that the Russian domestic production of Iranian-designed drones at the Alabuga site will increase to about 6,000 drones a month in 2025 (Albright et al., 2023). Figure 2 shows the predicted drone capacity of the Alabuga site through August 2025.

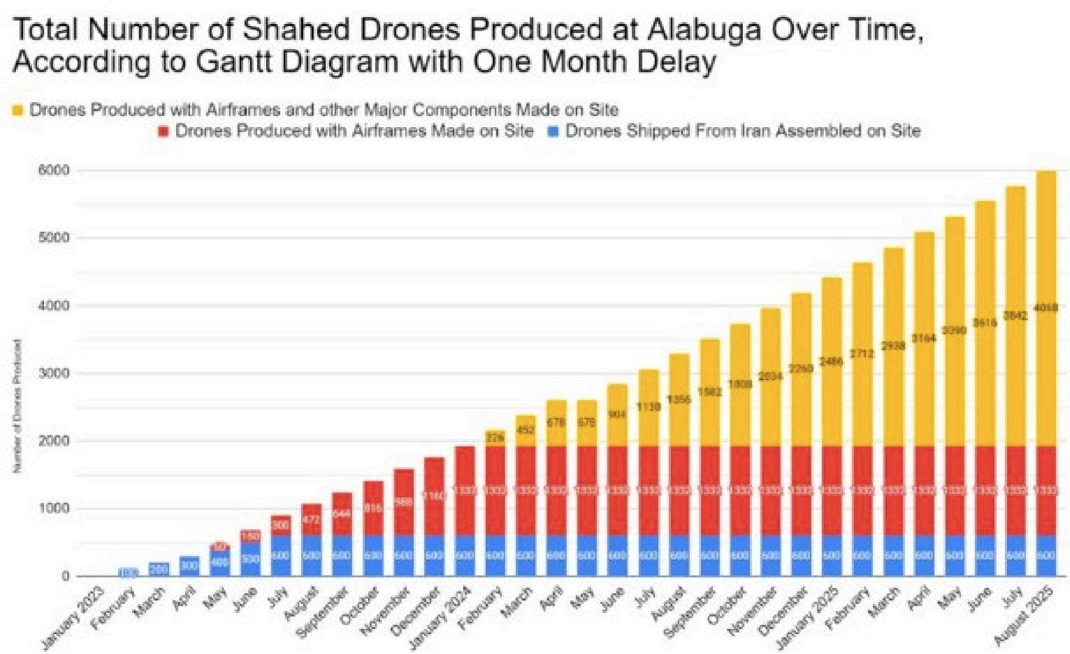


Figure 2. Drones Production in Russia During War with Ukraine. Source: Albright et al. (2023).

Similarly, China's supplies to Russia are becoming more significant. China denies providing military support to Russia however PRC based firms are providing critical 'dual use' materials that help sustain Russia's war effort. In 2023 trade between the two countries was up over 64% from before the beginning of the war (Ng & Ma, 2024). Figure 3 shows the increased trade between China and Russia. China exports over $300 million worth of dual use materials to Russia monthly. Currently, 90% of microelectronics and 70% of machine tools that are imported by Russia come from China (Ng & Ma, 2024). The U.S. Department of the Treasury has imposed sanctions on over 300 entities and individuals supporting Russia's defense industry specifically targeting firms that support the Russian UAS procurement network (U.S Department of the Treasury, 2024b). On October 17, 2024, sanctions were imposed on two Chinese companies for directly supplying Russia with PRC designed, developed, and produced drones. The Garpiya drone is manufactured in China in collaboration with Russian defense entities. The drones have been deployed into Ukraine by Russia and were used to destroy critical infrastructure and caused mass causalities (U.S Department of the Treasury, 2024c).

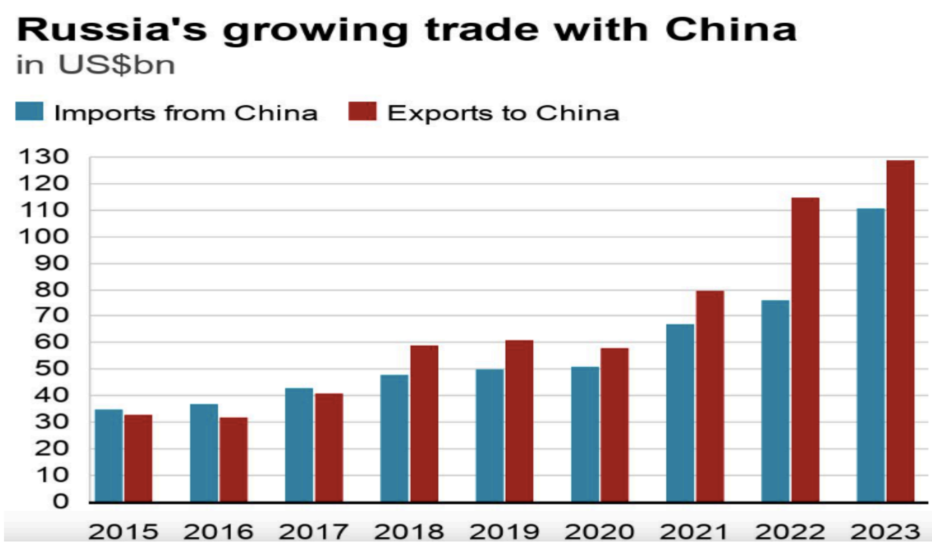


Figure 3. Russia's Trade with China since 2015.
Source: Ng and Ma (2024).

As the war progresses both Russia and Ukraine are ramping up production of long-range drones and the line between traditional missiles and drones is becoming blurred. Ukraine has successfully developed and deployed long-range attack drones that have stuck Russian military targets inside Russia. Such attacks are becoming more prevalent as Ukrainian drone technology progresses. In one such attack, Ukrainian forces successfully attacked a military depot about 300 miles from the Ukrainian Russian boarder. Reportedly, over 100 Ukrainian made drones were used in the attack (Arhirova, 2024). In May 2024 a Ukrainian intelligence source revealed that Ukraine's longest range drone attack targeted an oil processing facility 932 miles away in Russia's Bashkiria region (Reuters, 2024). On August 24, 2024, Ukrainian President Volodymyr Zelenskyy disclosed the first successful combat use of the Palianytsia, a domestically designed single use missile-drone capable of striking static Russian targets (Zelenskyy, 2024). The Palianytsia has a turbojet engine and a range of at least 370 miles (Hambling, 2024b). The range of the weapon puts at least 24 Russian airfields within its striking range. The Palianytsia is reportedly cheaper than counterpart weapons and was rapidly developed within a year and a half (Zelenskyy, 2024).

Despite Ukraine's rapid drone development keeping parity with Russian capabilities continues to be a challenge. As soon as Ukraine develops tactics, techniques, and procedures (TTP) using drones, Russia soon copies. Due to Russia's military industrial base and supplier network, it can manufacture drones in mass which erodes Ukraine's tactical gains (Coles & Sivorka, 2024). Pentagon press Secretary Maj. Gen. Ryder continues to stress that Ukraine urgently needs the capabilities required to defend against Russian launched missiles and drones (Lopez, 2024a).

The conflict in Ukraine has given a glimpse into the role drones and technological innovations may play in future warfare. As the war continues the DoD is quickly understanding that rapidly advancing drone technology may play a pivotal role in achieving tactical advantage in future conflicts. Additionally, that pace of expenditures calls into question whether current U.S. military inventories are sufficient and if the U.S. military industrial complex can replenish supplies cost effectively and fast enough.

C. ISRAEL

On October 7, 2023, Hamas militants crossed the Israeli border from Gaza and killed an estimated 1,200 people and took another 250 as hostages. The attack highlighted the vulnerability of a well-established defense force against a low-cost low-tech drone attack (Butterworth-Hayes, 2023). In response, Israel launched a military offensive into Gaza supported by air strikes and followed by a ground invasion (BBC, 2024b). Since then, the war has escalated into a regional conflict with Iran and their proxies across the Middle

East. Iran is largely believed to be financing Hamas, Hezbollah, and Houthi war efforts. Iran's support includes providing weapons and training soldiers (Biesecker, 2024). The United States continues to provide security and defense aid to Israel.

Hamas' weapons are a mix of domestically made armaments that are constructed from commercial off-the-shelf (COTS) materials and conventional weapons largely from Iran, China, Russia, and North Korea (Biesecker, 2024). Among Hamas' domestically produced arsenal are the al-Zuwari drone and Qassam rocket. The al-Zuwari is a kamikaze style drone. Hamas claims it used 35 of these drones to strike Israeli observation towers during the October 7 attack (Biesecker, 2024; Butterworth-Hayes, 2023). Hamas also stated they launched over 5,000 rockets during the attack (New Arab, 2023). For every $300 to $800 rocket Hamas launches it cost Israel around $50,000 to intercept (The New Arab, 2023). The Qassam is a crude rocket that is cheaply constructed out of industrial piping, fueled with a mixture of sugar and fertilizer, strapped with a commercial explosive, and then launched from homemade scaffolds or truck launchers (Hambling, 2023). The Qassam is relatively small and cheap and is estimated to cost between $300 and $800 per unit (The New Arab, 2023). It lacks targeting capability but can be effective as a form of harassing fire in the asymmetric war forcing Israel to expended Iron Dome missiles to intercept and destroy (Hambling, 2023). Additionally, Hamas is leveraging Chinese hobbyist quadcopter drones to manufacture anti-tank and anti-personnel bombs. They are also either using or copying Iranian-designed drones filled with explosive warheads to attack Israeli targets (Biesecker, 2024). Similar models of UAS have been reported to be in the possession of Hezbollah (Lappin, 2023).

One day after Hamas's attack on Israel, Hezbollah, the Lebanese militant group, fired rockets into Israel. Israel responded with military action and over the last year cross border tensions and kinetic engagements have continued to escalate. In July 2024 Israel assassinated Hezbollah commander Fuad Shukr and the following month on August 25, 2024, Hezbollah launch over 300 rockets at Israel (Young, 2024). Following the one-year anniversary of the October 7th attack Hezbollah launched two drones into Israel. One of which was able to go undetected by Israel's Iron Dome defense system and hit the Golani

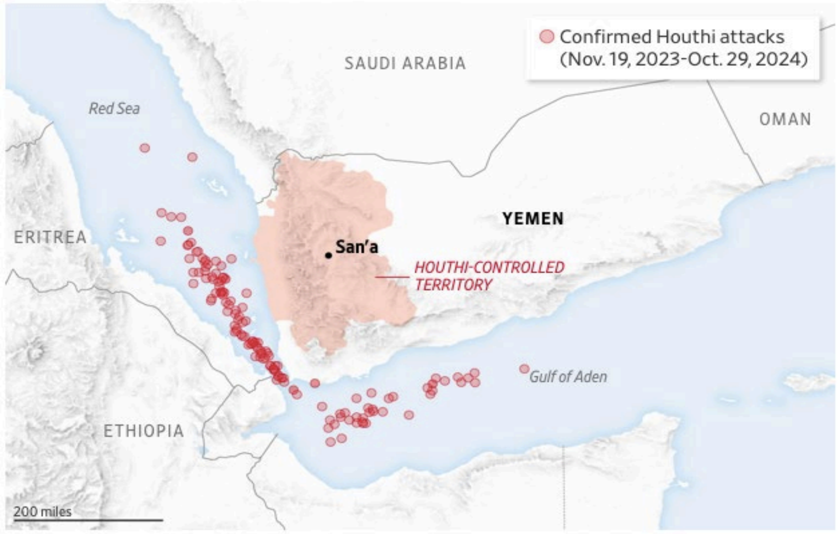
Brigade 40 miles inside Israel. The attack killed four IDF soldiers and seriously wounded seven more (Bob, 2024).

As the conflict continues the drone attacks into Israel are becoming more deadly. Since October 2023 Hezbollah has carried out hundreds of UAS attacks. It is estimated that Hezbollah has over 2,000 drones of various types (Frantzman, 2024). Hezbollah is likely using COTS quadcopters for surveillance. They have also turned drones into loiter munitions where they can be programmed with preplanned flight paths to hit established targets (Frantzman, 2024). Hezbollah also uses the Mirsad-1 and Mirsad-2 which are based on the Iranian Mohjer and Ababil. Mirsads have a range of 120 km and can carry around 40 kg of munitions (Frantzman, 2024). Additionally, Hezbollah relies on Iranian made UAS like the Ababil and Shahed-136. The Shahed-136 has become the mainstay drone of Iran and it proxies (Frantzman, 2024). The Houthis in Yemen have used the Shahed-136 to attack Tel Aviv and disrupt commercial shipping through the Red Sea. Figure 4 shows Shahed-136s being launched from a truck bed.

Figure 4. Shahed-136s Being Launched from a Truck. Source: Army Recognition Group (2024).

Since October 17, 2023, Iranian backed Houthis have used UAS and missiles to attack commercial vessels in the Red Sea at least 53 times. Figure 5 shows the confirmed Houthi attacks in the Red Sea between November 12, 2023, and October 29, 2024. These attacks have disrupted global supply chains and have forced commercial suppliers to divert their shipments to longer and more expensive sea routes around Africa (Congressional Research Service, 2024). Between October and December 2023 U.S. Navy destroyers shot down 38 drones expending critical ordnance that is estimated to cost up to $2.1 million a shot (Seligman & Berg, 2023). On December 16, 2023 alone, the USS CARNEY successfully shot down 14 Houthi launched attack drones. The Houthi drones they were countering only cost an estimated $2,000-$20,000 a piece to produce (Pilkington, 2023). The Houthis can produce 105–1,050 drones for the cost of one missile that the U.S. uses to destroy them.

Attacks in the Red Sea



Note: Houthi territory is as of May 13, 2024.
Sources: Acaps (Houthi territory); The Washington Institute for Near East Policy (attacks)
Emma Brown/THE WALL STREET JOURNAL

Figure 5. Houthi Controlled Territory Relative to Red Sea Attacks. Source: Faucon and Strobel (2024).

The threat in the Red Sea is continuing to grow as the Houthis increase relations with al-Shabaab and al Qaeda terrorist groups. The Houthis have even agreed to transfer drones, rockets, and other explosives to al Qaeda entities (Faucon & Strobel, 2024). To exacerbate the problem, Russia has started to provide the Houthis data so they can more effectively target shipping vessel. Additionally, Russia is contemplating supplying the Houthis with antiship missiles (Faucon & Strobel, 2024). The asymmetric weapon exchange between the U.S. and the Houthis are disproportionally depleting the US's supply of expensive and high-tech ordnance. Draining critical ordnance inventories for such low-cost threats could be exploited by adversaries and hinder the US's strategic response in an imminent near peer conflict.

In addition to supporting Hamas, Hezbollah, and Houthi forces with UAS, Iran has launched its own attacks on Israel. Twice in the last six months Iran has sent a barrage of missiles and drones into Israeli air space. During the first assault in April 2024, the U.S. led a military coalition to assist Israel in intercepting more than 170 Iranian drones and 150 missiles (Federman & Gambrell, 2024). At the time, this was one of the largest drone strikes ever (Schwartz, 2024). Israel claims that all 170 drones were successfully intercepted. Most were stopped with its sophisticated air defense system, Arrow. The system is designed to shoot down ballistic missiles (Federman & Gambrell, 2024). The Shahed-136 drones that were used in the attack have an estimated speed of nearly 115 miles per hour making them much slower than higher end munitions and therefore easier to shoot down (Schwartz, 2024). Still, when launched in swarms they can stress air defense systems.

Iran fired a second round of 200 missiles into Israel on October 1, 2024, following the assassination of Hezbollah leader Hasan Nasrallah. Iran specifically targeted military installations. Two U.S. destroyers, the USS Bilkeley and USS Cole, fired a dozen interceptors to help defend Israel (Lopez, 2024b). Thomas Karako, the director of the Missiles Defense Project at the Center for Strategic and International Studies, cautions that in an hour the United States expended a year's worth of missile production (Brennan, 2024). Like the previous attack, Israel's air defense capabilities destroyed most of the missiles before they hit their targets.

Israeli Prime Minister, Benjamin Netanyahu, promised a military response and on 25 October Israel carried out a precision strike on Iranian military targets (Rubin & Nakashima, 2024; Lopez, 2024b). Israel's retaliatory strike marked the first time Israel has publicly launched an attack on Iran (Salem, 2024). In apparent anticipation of the escalating tit for tat strikes, the U.S. has provided Israel with a Terminal High-Altitude Area Defense (THAAD) battery system. The THAAD capabilities are roughly the same as Israel's Arrow system. It is designed to counter short to intermediate-range ballistic missiles. Its target range is 93–124 miles and can intercept missiles in and outside the earth's atmosphere (Brennan, 2024). However, the system's use will be limited by lack of interceptor missiles. Each THAAD system is equipped with 48 missiles. In December 2023 Lockheed Martin acknowledged it had only delivered 800 interceptor missiles to the DoD (Brennan, 2024). Still, U.S. Secretary of the Army, Christine Wormuth, stated that the deployment of the $1 billion system and 100 U.S. service members required to operate the system are a visible sign of the United States' commitment to support the defense of Israel (Brennan, 2024).

Since Israel's founding in 1948 the U.S. has provided over $130 billion in assistance focused on addressing security threats and maintaining a Qualitative Military

Edge (QME) (U.S. Department of State, 2023). Israel is the leading recipient of American Foreign Military Financing (FMF) which allows allies and partners to purchase U.S. military equipment. A ten-year Memorandum of Understanding (MOU) was signed in 2019 which provides Israel with $3.3 billion in FMF and another $500 million for missiles defense programs, annually (U.S. Department of State, 2023). The MOU allows Israel to use a portion of the FMF on Israeli made defense articles instead of purchasing from American firms. Additionally, the U.S. has exported over $12.2 billion in defense articled through Direct Commercial Sales (U.S. Department of State, 2023). In April the House of Representatives passed the Israel Security Supplemental Appropriations Act, 2024 which provided an additional $26.38 billion to support the defense of Israel and replenish critical munitions including $4 billion for Iron Dome and David's sling replenishments (Appropriations Chairman Tom Cole Press release, 2024)

Still, despite the financial and military support of the U.S. and the success of Israel's robust air defense systems, the missile-based strategy to stop low-cost drones is stressing both Israel's and the United States' defense inventory. A former U.S. Defense official, Dana Stroul, argued another large airstrike from Iran could stretch Israel's defense capabilities (Rathbone, 2024). Israel may soon be facing a shortage of Iron Dome interceptor missiles (Rathbone, 2024). The U.S.-provided THAAD will provide some short-term reprieve but both U.S. and Israeli munitions production are not keeping pace with expenditures. Both Raytheon and Lockheed Martin acknowledge that even with new multi-year contracts it will take over five years to build the inventory back to the pretransfer levels (Gureck, 2023). With more than 20,000 projectiles shot at Israel since October 2023 and missile production rates remaining below expenditures Israeli air defense planners will soon have to prioritize areas to defend (Rathbone, 2024).

In sum, the United States' ability to supply both Israel and Ukraine and maintain a sufficient national military stockpile of munitions could soon become unsustainable.

D. PEOPLE'S REPUBLIC OF CHINA

Russia would not be able to sustain its war effort in Ukraine without State sanctioned support from China. The U.S. has sanctioned Chinese firms aiding Russia's war effort, but the sanctions have not deterred increased relations between the two nations. In addition to enabling Russia the PRC is also increasing its trade relations with Iran. Today, China is Iran's largest trade partner (Lu, 2024). Jon Alterman, the director of the Middle East studies program at the Center for Strategic and International Studies, suggests China is the country with the greatest possible influence over Iran (Lu, 2024). Oil trade between the two nations has tripled since 2020 and is helping to fund Iran's weapon's program (Lu, 2024). This year also marks the 75th anniversary of the PRC's bilateral relationship with North Korea. The anniversary has spurred renewed declarations of cooperation and exchange. Over 90 percent of North Korea's import and exports come from China (Fong & Albert, 2024). China's expanding relations with Russia, Iran, and North Korea only heightens concern over the growing tensions between China and Taiwan.

The PRC has long held territorial claims over Taiwan. Much like Putin's messaging around Ukraine, Xi Jinping asserts Taiwan must be reunited with mainland China (Sacks, 2022). In 2024, William Lai was elected as the president of Taiwan. The PRC has largely branded Lei as a separatist. Twice since his election earlier this year the PRC has held major military exercises simulating a full-scale invasion of Taiwan (BBC, 2024a). While the PRC's calculation for when to pursue forceful unification may not be changed by the ongoing conflicts in Ukraine and Israel, they are keenly observing the events and looking for lessons that could be applicable if a future conflict over Taiwan arises (Sacks, 2022). The PRC leadership and the People's Liberation Army (PLA) will be studying Russia's invasion of Ukraine and will likely adjust their operational plans to prevent similar mistakes. Among those lessons is Russia's failure to gain air superiority over Ukraine (Sacks, 2022).

The PRC understands that drones are changing modern warfare and are heavily investing in expanding their military drone capabilities and capacity. The PRC is developing over 50 drone variates and are focused of creating a fleet of drones that can over match the capabilities of Taiwan and the United States (Michaelson, 2024). China currently dominates the commercial drone industry. Chinese firm DJI alone accounts for 76% of all worldwide commercial drones on the market. The current production capacity and domestic availability of low-cost drones helps provide China the edge in modernizing and amassing a massive fleet of military drones (Michaelson, 2024).

China is also aware of the US's reliance on high-end weapons and their doctrine plans to exploit this dependency (Koffler, 2023). To this end, China is working to create a military proficient in overwhelming U.S. capabilities. If China did launch a full-scale attack on Taiwan, they would likely use inexpensive technology like UAS swarms in parallel with high-end weapons to overwhelm Taiwanese forces and to compel the U.S. military to expend large numbers of critical munitions early in the order of battle to counter the assault (Gureck, 2023). If China was to employ such tactics the U.S. Navy would be hampered in its ability to sustain combat effectiveness due to munition limitations and rearming constraints. This problem would be compounded by limited national inventories and sluggish missile production rates. This would leave the U.S. in a vulnerable position in a protracted conflict.

E. UNITED STATES

In August 2023, the DoD launched the Replicator Initiative to address the increasing threats posed by drones. The Replicator Initiative secured $500 million in funding to achieve its objective to accelerate the production of low-cost, attritable drones that can be launched in mass to saturate the battlespace and overwhelm an enemy (Magnuson, 2024). The goal is to field thousands of low-cost autonomous drones within 24 months. The Replicator Initiative supports U.S. INDOPACOM Commander, Admiral Paparo's "hellscape" strategy which envisions deploying thousands of air and sea based UAS to deter Chinese aggression towards Taiwan (Michaelson, 2024).

The project is creating an accelerated framework to deliver critical capabilities to warfighters faster. The Replicator Initiative also gives greater flexibility for leveraging prototyping and experimentation. It allows for faster acquisitions of non-traditional defense technologies and allows for a more diverse vendor base (Defense Innovation Unit, n.d.). The Replicator Initiative relies on commercially developed solutions and provides demand signals to commercial companies to encourage building up in the military industrial base (Defense Innovation Unit, n.d.).

In May 2024 AeroVironment's Switchblade 600, a tube launched drone that weighs roughly 33 pounds and has a range of about 29 miles was selected for tranche one of the projects (Magnuson, 2024). Figure 6 shows the Switchblade 600's capabilities. The program plans to take AI chips and military software and put them into commercial drones to get the prices down from around \$3,000 to \$6,000 per unit. Currently, U.S. made kamikaze style drones cost around \$60,000 per unit through normal DoD procurement channels (Wang, 2023). You might wonder why the current drones are so expensive. What drives the \$60,000 per unit price tag? Deputy Secretary of Defense, Kathleen Hicks, has touted the Replicator Initiative by stating that it validates that the DoD can encourage the delivery of new capabilities quickly and at scale (Defense Innovation Unit, 2024).

Figure 6. Switchblade 600. Source: Wang (2023).

In December 2023 President Biden signed the National Defense Authorization Act for Fiscal Year 2024 (NDAA). This year's NDAA includes several statutory changes that allow for important and much needed acquisition policy reform (Coffey et al., 2024). Section 229: Rapid Response to Emergent Technology Advancements or Threats, provides the Secretary of Defense (SECDEF) with the authority to use the rapid acquisition pathway to leverage new technologies to address emerging threats (Coffey et al., 2024). This change could allow for operational development of c-UAS systems that use innovative technology such as additive manufacturing.

F. ADDITIVE MANUFACTURING

Additive manufacturing, also known as 3D printing, is a rapidly maturing technology that allows for functional products to be created directly by inputting model designs into a computer aided design (CAD) program. The software transfers the design into a layer-by-layer model that a 3D printer can print immediately (Linke, 2017). 3D printing offers enticing cost and time saving advantages over traditional manufacturing methods which can often only recoup high upfront investment with high production rates. Additive manufacturing removes many of the intermediate supply chain processes which can save on operational cost and speed up delivery times (Linke, 2017). It also provides opportunities for customization with little cost implication. Still, additive manufacturing has a unique set of challenges. The machines involved can be extremely expensive. Additionally, 3D printing can be slower than traditional manufacturing methods when creating larger amounts of a particular product and the process can also have significant quality control issues (Linke, 2017). Quality control would likely be the largest issue in applying the process to the production of sensitive and precise weapons systems. Nevertheless, persistent attempts at implementation continue. On October 22, 2024, X-Bow Systems Inc successfully launched the Bolt Rocket for the third time (PR Newswire, 2024). The rocket which was sponsored by DIU and U.S. Army Space and Missile Defense Command is equipped with a XB-32 motor. The XB-32 is the largest Advanced Manufactured Solid Propellant (AMSP) motor to have ever flown (PR Newswire, 2024). The launch demonstrates that 3D print rockets are achievable.

Despite quality control concerns, additive manufacturing has already been successfully used in space rocket production and on the battlefields in Ukraine. The DoD has recently contracted Ursa Major to build the U.S. Navy's Mk104 rocket motor which goes into SM-2, SM-3s, and SM-6s. These rockets currently cost between \$2.1-\$4.87 million per unit and due to production bottlenecks, the U.S. Navy only acquires 125 SM-6s a year (Hambling, 2024a). The company uses additive manufacturing to replace traditional rocket casing methods (Hambling, 2024a). The CEO of Ursa Major, Joe Laurienti, explains that traditional rocket casings are made by an extruder which uses extreme force to form metal into a tube with no welding seam. This is important because rocket motor casing must be able to withstand extreme temperature and pressure. There are only a few extruder machines in the U.S. creating a production bottleneck (Hambling, 2024a). Ursa Major has leveraged commercial 3D printed to eliminate the need for an extruder and other production processes used in traditional rocket manufacturing (Hambling, 2024a). 3D printing offers the potential to manufacture rocket motors at a faster rate than current production methods and opens the possibility to create new weapons that are impossible with traditional manufacturing methods (Hambling, 2024a). On March 22, 2023, Relativity Space launched the first 3D printed rocket, the Terran 1, into space. However, the rocket failed to reach orbit after experiencing an issue three minutes after takeoff (Sheetz, 2023). Relativity Space is now developing the Terran R rocket that incorporates aluminum alloy into the 3D printing process. The Terran R is expected to launch in 2026 (Sheetz, 2023). Still, 3D printing in weapons manufacturing is largely untested and rigorous analysis is needed to establish if 3D printing can reduce manufacturing timelines, production costs, and resupply challenges for defensive missiles.

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III. METHODOLOGY

A. INTRODUCTION

The United States military depends on the Cost Assessment Data Enterprise (CADE) system for comprehensive and accurate project cost estimation. While CADE serves as a powerful centralized repository that combines historical data, current program information, and advanced estimation models, it faces notable limitations when evaluating certain defense platforms, particularly in rocket development and production.

This chapter explores these challenges through a methodical analysis of c-UAS rocket costs. Using both single-variable and multivariable regression analyses, we examine how two key factors – labor hours and range influence the overall cost of these defense systems. For this analysis, labor hours will be measured in total labor hours (Hrs) for rocket each iteration (*i)* of rocket produced. Range will be measured in meters (M).

To establish a baseline for minimum production costs, we will analyze the H56 3D printed guided rocket prototype developed by USINDOPACOM J85. This innovative prototype constructed using COTS materials, demonstrates the potential for cost-effective manufacturing of 2.75-inch class rockets. However, since 3D printing represents a novel approach to defense rocket manufacturing, comprehensive cost comparison data remains limited. Due to the classification of missile specifications and immaturity of 3D printing in rocket production it would be difficult to quantify effectiveness for c-UAS missiles only using monetary evaluations. Therefore, it is not feasible for the purpose of this analysis to convert all of the relevant variables into costs.

B. DATA COLLECTION

The following variables have been collected for the analyses:

Dependent Variable:

- Total cost of c-UAS rockets (in USD)

Independent Variables:

- Labor hours

- Range

C. SAMPLE SIZE AND DATA AVAILABILITY

Currently, the available data for this study is limited to four known data points with three projected costs for c-UAS rocket systems. This sample size is considerably smaller than what would typically be required for robust statistical analysis, which presents significant challenges for the proposed regression analyses.

The analyses methods will be exploratory and descriptive in nature because the sample size is so small. Statistical inference and predictive modeling capabilities are severely limited. Therefore, the results should be interpreted with extreme caution and viewed as preliminary findings.

D. SINGLE-VARIABLE REGRESSION ANALYSIS

Two separate simple linear regression models have been constructed:

$\text{Total Cost}_i = \beta_0 + \beta_1(\text{Hrs})_i + \varepsilon_i$

$\text{Total Cost}_i = \beta_0 + \beta_1(\text{M})_i + \varepsilon_i$

where:

- β_0 is the y-intercept
- β_1 is the slope coefficient
- ε is the standard error term

E. MULTIVARIABLE REGRESSION ANALYSIS

A multiple linear regression model has been constructed using both independent variables:

$\text{Total Cost}_i = \beta_0 + \beta_1(\text{Hrs})_i + \beta_2(\text{M})_i + \varepsilon_i$

where:

- β_0 is the y-intercept

- β_1 and β_2 are the regression coefficients
- ε is the standard error term

F. ESTIMATION METHOD

The Ordinary Least Squares (OLS) method was used to estimate the regression coefficients.

G. MODEL EVALUATION

For each model, the following has been calculated and interpreted:

1. R-squared Value

The R-squared value functions as the model's overall performance, quantifying how effectively our chosen variables explain variations in cost. This metric is particularly valuable in cost modeling where multiple competing models might exist for the same system. For instance, when predicting c-UAS rocket costs, an R-squared of 0.85 would indicate that our model accounts for 85% of the observed cost variations, leaving only 15% unexplained by our selected variables. While higher values suggest better explanatory power, the R-squared must be considered alongside other metrics in the model evaluation hierarchy (Mislick & Nussbaum, 2015). When comparing models with different numbers of independent variables, analysts should use the Adjusted R-squared value instead, as it accounts for the artificial increase in R-squared that occurs when additional variables are added to the model (Mislick & Nussbaum, 2015). This adjustment ensures a fair comparison between models of varying complexity and prevents the selection of overfitted models that might perform poorly in actual cost predictions.

2. F-statistic and Its p-Value

The F-statistics are critical in evaluating the collective significance of all variables in the model. While variables may appear individually significant, the F-statistics assess their combined explanatory power in predicting the dependent variable. When examining COTS costs, for this example, this would determine whether factors like labor, range, and the future prospective of payload collectively create a meaningful predictive model. The significance value ($p < 0.10$) indicates whether these relationships could have occurred by chance (Mislick & Nussbaum, 2015). A smaller p-value increases our confidence that the observed relationships truly indicate the desired results and not random instances of wavering in the data, allowing us to prefer the regression model over simply using average values calculated across the separate rocket iterations.

3. T-statistics and p-Value for the Slope Coefficient

The t-statistics provide an examination into the details of each variable's contribution to the model, acting as a quality control measure for individual predictors. This is valuable when analyzing COTS systems where multiple factors could create complexities that inadvertently influence cost. A significance level ($p < 0.10$) for each variable ensures that we only retain meaningful predictors in our model (Mislick & Nussbaum, 2015). This selective approach prevents the inclusion of illegitimate variables that might appear important but add noise to our predictions. In simpler models with just one predictor, the t-statistic and F-statistic significances align numerically, differing only due to their underlying statistical distributions (Mislick & Nussbaum, 2015).

By analyzing these metrics together, we can gain a comprehensive understanding of each model's statistical significance, explanatory power, and the reliability of its coefficients. This will allow us to make informed comparisons between models and draw sound conclusions about the relationships we are investigating.

IV. ANALYSIS

A. INTRODUCTION

This chapter presents an examination of the relationships between the total cost of a single c-UAS rocket and two key variables: labor hours and range. The analysis employs progressively complex regression models to understand these relationships, beginning with simple linear regressions and culminating in a multiple regression analysis. To ensure the data supported our conclusions, we evaluated the same key statistical metrics: R-squared values to assess explanatory power, F-statistics to evaluate model significance, and t-statistics to determine the reliability of individual variable coefficients.

B. STATISTICAL ASSUMPTIONS

Several critical assumptions were also developed during our research to ensure the validity and reliability of regression analysis used in the final cost estimation. Each assumption provides a foundational element required for sound statistical analysis and inference.

1. Linearity Assumption

The analysis assumes linear relationships exist between the independent variables (labor hours and range) and the dependent variable (total cost per unit). This means that changes in labor hours or range should result in proportional changes in cost. The linearity assumption is fundamental to the regression framework and implies that the relationship between variables can be adequately represented by straight lines (Montgomery et al., 2021). Any significant deviation from linearity could lead to biased estimates and unreliable predictions.

2. Independence of Observations

Each data point must represent an independent unit developed. This assumption requires that there be no systematic patterns or relationships between successive observations. In the context of production cost analysis, this means that the cost associated with one production instance should not influence or be influenced by the costs of other instances (Cohen et al., 2013). This independence is crucial for the validity of statistical tests and confidence intervals.

3. Absence of Perfect Multicollinearity

In multiple regression models, there must be no perfect correlation between independent variables. This assumption is essential for distinguishing the individual effects of each variable on cost (Cohen et al., 2013). Perfect multicollinearity would make it impossible to determine the unique contribution of each variable to cost variation, undermining the model's interpretability and practical utility.

4. Representative Sampling

The analysis assumes that the sample adequately represents the broader population of production scenarios. This assumption is particularly challenging given the small sample sizes in cost estimation, but it is crucial for the generalizability of findings beyond these specific observations (GAO, 2020). The sample must capture the typical range of production conditions and cost outcomes for conclusions to be meaningful.

5. Sample Size Adequacy

One of the most critical assumptions is the adequacy of sample size (Mislick & Nussbaum, 2015). While statistical analysis is possible with limited datasets, small sample sizes reduce statistical power and increase the margin of error in estimates. This limitation suggests that results should be interpreted with appropriate caution and validated with additional data when available. In this case, because the sample size was only four rocket iterations, we used cost and range data from Table 1 to project COTS costs for impulse range N and O based on future capability advancements.

Table 1. Rocket Propulsion System Costs and Heights

Classification	Impulse Range	Impulse Limit (N-s)	Category	Rough $	Mass (g)	DIAM(MM)	max height(m)
Model Rocket	1/8A	0.3125	Micro				0.00
Model Rocket	1/4A	0.625	Low Power				0.00
Model Rocket	1/2A	1.25	Low Power				0.00
Model Rocket	A	2.5	Low Power				0.00
Model Rocket	B	5	Low Power				0.00
Model Rocket	C	10	Low Power				0.00
Model Rocket	D	20	Low Power				0.02
Model Rocket	E	40	Mid Power				0.07
Model Rocket	F	80	Mid Power				0.30
Model Rocket	G	160	Mid Power				1.19
High Power	H	320	LVL 1				4.74
High Power	I	640	LVL 1	140.8			18.98
High Power	J	1280	LVL 2	110.04			75.92
High Power	K	2560	LVL 2	201.15			303.66
High Power	L	5120	LVL 2	407.05			1214.64
High Power	M	10240	LVL 3	828.32			4858.57
High Power	N	20480	LVL 3	2083.84			19434.27
High Power	O	40960	LVL 3	8001.69			77737.08

6. Outlier Assessment

The analysis assumes that no significant outliers are distorting the relationship between variables. Given typical small sample sizes in cost estimation, the presence of even a single outlier could substantially impact results (Montgomery et al., 2012). We assume that all observations represent valid production scenarios and that any extreme values reflect genuine cost relationships rather than data anomalies.

The validity of these assumptions directly impacts the reliability of statistical inferences and the practical utility of cost estimation models. Regular assessment of these assumptions through statistical tests and visual diagnostics would be advisable as additional data becomes available (GAO, 2020). Furthermore, any application of these models should consider the degree to which these assumptions hold in the specific context of use.

C. 3D PRINTED ROCKET PRODUCTION LEARNING EFFECTS

The data presented in Figure 7 demonstrates a clear learning curve effect in the production of 3D printed rockets, showing a significant reduction in total labor hours across successive units. This pattern aligns with established learning curve theory in aerospace manufacturing, where labor hours typically decrease at a consistent rate as production experience accumulates (Mislick & Nussbaum, 2015).

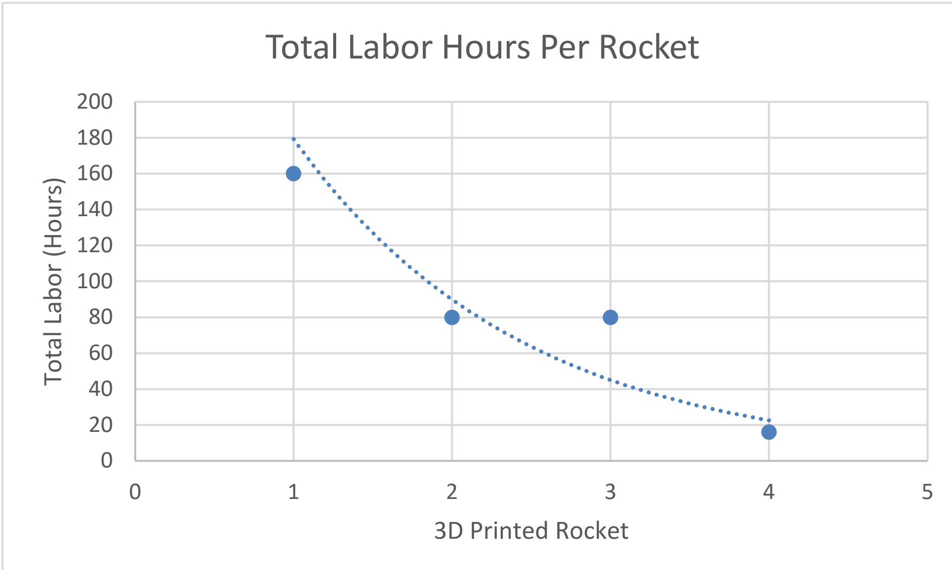

Figure 7. Total Labor Hours for Each Rocket Produced

From the first to the fourth rocket produced, labor hours decreased from approximately 160 hours to 16 hours – a reduction of nearly 88%. This steep learning curve is characteristic of innovative manufacturing processes, particularly in aerospace applications involving advanced technologies like 3D printing (Wong & Hernandez, 2012). The rapid improvement reflects NIWC PAC was able to optimize processes, create familiarity with technology designs, and refine their rocket parameters with each new iteration. The accelerated learning seen in this c-UAS rocket development emphasizes the draw of 3D printing technology, which enables rapid iteration and process improvement through data-driven optimization.

D. ANALYSIS OF LABOR HOURS VS. TOTAL COST

The investigation begins with an examination of how labor hours influence total cost. To facilitate this analysis, Table 2 and Table 3 present the key statistical measures derived from the linear regression model of labor hours against total cost.

Table 2. Labor Hours vs. Total Cost Equation Results

Coefficient	Values
β_0	4988.09
β_1	49.96
ε	2959.41

Table 3. Labor Hours vs. Total Cost Regression Metric Results

Metric	Threshold	Values
R^2		0.5418
F-Stat p-value	<.1	0.0953
T-stat p-value (Labor Hours)	<.1	0.0953

The results reveal a moderate relationship between labor hours and total cost. The R-squared value of 0.5418 indicates that labor hours alone explain 54.18% of the variation in total cost, suggesting that while labor hours contribute substantially to cost determination, they tell only part of the story. This moderate explanatory power implies that other factors play important roles in determining total cost. Using this model, we'd use the following equation for future rocket cost estimation: Total Cost = 4988.09 + 49.96 (Hrs) +/- 2959.41.

The model's F-statistic p-value of 0.0953, while not meeting the conventional 0.05 significance threshold, achieves marginal significance at the 90% confidence level. This suggests that the relationship between labor hours and cost, while not definitively established at the highest confidence levels, is unlikely to be purely random. The t-statistic p-value matches the F-statistic at 0.0953, indicating that each additional labor hour associates with a $49.96 increase in cost, though this relationship carries moderate uncertainty.

Several limitations of this model warrant consideration. The moderate predictive power suggests missing variables, while the marginal statistical significance increases uncertainty in the model's predictions. Additionally, the assumption of a linear relationship between labor hours and cost may not hold across all ranges of production.

E. ANALYSIS OF RANGE VS. TOTAL COST

Following the labor hours analysis, we examined the relationship between range and total cost. Table 4 and Table 5 present the statistical results from this linear regression model.

Table 4. Range vs. Total Cost Equation Results

Coefficient	Values
β_0	7744.40
β_1	0.02
ε	4322.30

Table 5. Range vs. Total Cost Regression Metric Results

Metric	Threshold	Values
R^2		0.0225
F-Stat p-value	<.1	0.7766
T-stat p-value (Range)	<.1	0.7766

The results from this model paint a different picture from the labor hours analysis. The extremely low R-squared value of 0.0225 indicates that range alone explains only 2.25% of the variation in total cost, leaving an overwhelming 97.75% of cost variation unexplained. This suggests that range, when considered in isolation, provides virtually no predictive power for cost estimation. Using this model, we would use the following equation for future rocket cost estimation: Total Cost = 7744.4 + .02 (M) +/- 4322.3.

The model's F-statistic p-value of 0.7766 exceeds any conventional significance level. This high p-value suggests that the observed relationship between range and cost could be entirely attributable to random chance. The matching t-statistic p-value indicates that the estimated effect of range on cost ($0.02 per unit) is statistically indistinguishable from zero.

These results suggest that range alone cannot serve as a reliable predictor of cost in this context. The model fails to meet basic utility criteria for cost estimation purposes, exhibiting negligible explanatory power and a complete lack of statistical significance.

F. ANALYSIS OF MULTIPLE REGRESSION MODEL

Given the limitations of both single regression models, we next examined a multiple regression model that incorporates both labor hours and range as predictors of total cost. Table 6 and Table 7 present the statistical results from this combined model.

Table 6. Multiple Variable Regression Equation Results

Coefficient	Values
β_0	2218.35
β_1 (Labor Hours)	72.53
β_2 (Range)	0.09
ε	1689.21

Table 7. Multiple Variable Regression Analysis Results

Metric	Threshold	Value
R^2		0.8880
F-Stat p-value	<.1	0.0375
T-stat p-value (Labor Hours)	<.1	0.0171
T-stat p-value (Range)	<.1	0.0556

The multiple regression model demonstrates substantially improved predictive power compared to either simple regression model. The R-squared value of 0.8880 indicates that the combined model explains 88.80% of the variation in total cost, leaving only 11.20% unexplained. This improvement in explanatory power suggests that the interaction between labor hours and range captures important cost dynamics that neither variable alone could explain.

The model achieves statistical significance at the 90% confidence level, as evidenced by its F-statistic p-value of 0.0375. This provides strong evidence for the model's overall validity and suggests that the combined predictive power is highly unlikely to be random. The t-statistic p-value of labor hours and range respectively are .0171 and 0.0556 for the combined effects which were both within the 90% confidence interval threshold that we evaluated for.

The coefficient estimates from the multiple regression model suggest that, holding range constant, each additional labor hour corresponds to a $72.53 increase in cost, while each unit increase in range contributes an additional $0.09 to the cost, holding labor hours constant. These estimates are more precise than those obtained from the simple regression models, providing a more reliable basis for cost prediction.

G. COMPARATIVE ANALYSIS AND MODEL SELECTION

The multiple regression model demonstrates clear superiority in several crucial aspects. Its R-squared value of 0.8880 represents a 34.62 percentage point improvement over the labor hours model and an 86.55 percentage point improvement over the range model. It is the only model to achieve statistical significance at the conventional 95% confidence level, and it provides the most precise coefficient estimates.

The evidence overwhelmingly supports the selection of the multiple regression model for cost estimation purposes. While labor hours alone provide moderate predictive power, and range alone offers minimal insight, the combination of both variables creates an interactive effect that substantially improves our ability to predict costs. The multiple regression model's superior explanatory power, statistical significance, and more precise coefficient estimates make it the most reliable framework for understanding and predicting cost behavior in this context.

1. Applied Cost Estimation Analysis

When applying this model to an example scenario with:

- Stabilized labor hours at 16 hours (reflecting learning curve maturity)
- Target range capability of 10,000 meters

The cost estimate calculation becomes: \$2,218.35 + \$72.53(16) + \$0.09(10,000) ± \$1,689.21 = \$2,218.35 + \$1,160.48 + \$900 ± \$1,689.21 = \$4,278.83 ± \$1,689.21

This yields:

- Upper bound: \$5,948.86
- Lower bound: \$2,570.43

2. Strategic Implications

This cost range provides decision-makers with a framework for budgeting and risk assessment. The model's inclusion of both labor and performance parameters enables a trade-off analysis between operational capabilities and resource allocation. The confidence interval, calculated by (\$1,689.21 ÷ \$4,278.83) × 100, represents approximately ±39.5% of the cost estimate. This reflects the uncertainty in innovative advanced technology development while providing actionable boundaries for financial planning.

These findings have important practical implications for INDOPACOM to use in their future cost estimation processes. They suggest that both variables should be considered in conjunction when developing cost estimates. Regular validation of the model with new data and consideration of additional variables may further improve its predictive capacity.

The analysis provides a strong foundation for understanding the complex relationships underlying cost determination, while also suggesting directions for future refinement and improvement of the cost estimation process. Additionally, it should be noted that during testing, there was no warhead incorporated into the rocket design, a cost that exceeds everything if conventional design and suppliers are used. The combination of weight and cost could drastically impact the rocket performance and reliability of the cost estimations.

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V. CONCLUSION

A. SUMMARY OF WORK AND FINDINGS

This thesis sets out to assess how the DoD could cost-effectively counter high-volume low-cost drone threats. This study examined how low-cost drones are currently being used in Ukraine, Israel, and the Red Sea. It explored the risks posed by the PRC's use and expanding capacity for military-capable drone production. The research then examined how additive manufacturing is currently being used to build military grade weapons. Finally, the study assessed U.S. INDOPACOM's prototype rocket to analyze how much it costs to build a military-capable 2.75inch rocket using 100% COTS material and 3D printing.

Our study strongly supports selecting the multiple regression model for the creation of the prototype's cost estimate. This model demonstrates substantially improved predictive power compared to either simple regression model attempted. The analysis shows there is a learning curve to building rockets. It indicates that labor hours per rocket decrease over time. However, as the cost for labor decreases the cost for additional range increases the cost per rocket. We hypothesize that as new variants of the rocket are designed with increased capabilities including range there will be increases in the labor hours required followed by a benefit of scale of economy. This would require further analysis to validate.

The prototype has only been launched four times, which significantly limits the data available with which to run the analysis. The small data set impacts reliability and limits the statistical significance of the finding. As such, the findings of this study should be interpreted with caution and viewed as exploratory research requiring further examination as data becomes available. Still, despite these data challenges, the research suggests the rapid rate of iterative design that is enabled by 3D printing technology can result in decrease labor hours.

B. FUTURE RESEARCH

The original intent of the study was to compare the prototype to other c-UAS systems currently in the U.S. inventory. Through a cost effectiveness analysis (CEA) the study was going to include additional variables beyond range and labor hours to assess the value of using 3D printing technology and COTS material to produce a rocket. However, due to the limited availability of data the project scope shifted. In the future, when more data is accessible, research should be done comparing the prototype to legacy systems to determine meaningful tradeoffs between options.

Additionally, our study did not address the production time increases that would occur because of acquisition pathway decisions, munition safety and standard requirements, or supply chain restrictions. These variables would have cost implications for rocket production. Future studies should explore the impact these variables have on the cost of legacy rockets and determine options to potentially lower cost in the future.

Finally, over the course of our research we learned of numerous similar projects in the works. There are low-cost rocket efforts that are being developed with industry as part of the Replicator Initiative, there is another rocket effort at MIT, and one at Naval Postgraduate School (NPS). In the future, an analysis should be done comparing the various projects to see if the cost estimate treads that were observed while studying the prototype hold true across each rocket production. This study could shed light on larger cost trends and inform strategic decisions about adoption and full-scale production of any of these projects.

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