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SELF-PROPELLED WHEELED HOWITZER FOR MARINE CORPS USE: CAPABILITY-BASED ASSESSMENT

by

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The U.S. Marine Corps artillery community faces a growing capability gap in relation to peer adversaries, such as China and Russia, threatening its effectiveness and survivability in future conflicts. The Marine Corps' primary artillery system, the M777 towed howitzer, fails to provide the necessary firepower, mobility, and transportability required in future engagements. Wheeled artillery platforms present an opportunity to close these capability gaps, offering improved mobility and firepower, while remaining transportable enough for expeditionary operations. This study compares the M777 against various wheeled howitzer systems and concepts using a capabilities-based assessment approach. The wheeled howitzers outperformed the M777 in every metric, regardless of system requirement importance, challenging the effectiveness of towed artillery systems. The analysis identifies the Hawkeye, a truck-mounted 105 mm cannon, as the overwhelming favorite among the systems, despite its shorter range and smaller caliber. Hawkeye's lightweight design, high rate of fire, and ability to rapidly emplace and displace make it well suited for the expeditionary nature of the Marine Corps. Incorporating the Hawkeye, or another wheeled artillery system, into the artillery arsenal provides the Marine Corps with an improved artillery capability needed for future conflicts.

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SELF-PROPELLED WHEELED HOWITZER FOR MARINE CORPS USE: CAPABILITY-BASED ASSESSMENT

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LIST OF ACRONYMS AND ABBREVIATIONS

A2D2	anti-access area-denial
AHP	analytical hierarchy process
AGM	Artillery Gun Module
AOA	analysis of alternatives
ATACMS	Army Tactical Missile System
CBA	capabilities-based assessment
COTS	commercial-off-the-shelf
CRS	Congressional Research Service
EFSS	Expeditionary Fire Support System
FMTV	Family of Medium Tactical Vehicles
GAO	Government Accountability Office
GCE	ground combat element
GMLRS	Guided Multiple Launch Rocket System
HIMARS	High Mobility Rocket System
HMMWV	High Mobility Multipurpose Wheeled Vehicle
ISR	intelligence surveillance and reconnaissance
JLTV	Joint Light Tactical Vehicle
KMW	Krauss Maffei Wegmann
KPP	key performance parameter
LAR	light armored reconnaissance
LCAC	landing craft air cushioned
LCU	landing craft utility
MAGTF	Marine Air Ground Task Force
MCDM	multi-criteria decision making
MEU	Marine Expeditionary Unit
MRSI	multiple round simultaneous impact
MTVR	Medium Tactical Vehicle Replacement
NDI	non-developmental item
NSFS	naval surface fire support
OEF	Operation Enduring Freedom

OIF	Operation Iraqi Freedom
OIR	Operation Inherent Resolve
PLA	People's Liberation Army
PM-TAS	Program Manager-Towed Artillery Systems
QFD	quality function deployment
RAP	Rocket Assisted Projectile
SLEP	service life extension program
UAV	unmanned aerial vehicle

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I. INTRODUCTION

The Marine Air Ground Task Force (MAGTF) has employed the M777 towed howitzer as its artillery workhorse for the past 15 years. First fielded by the Marine Corps in 2003, it provided rapid and accurate firepower in Operation Iraqi Freedom (OIF), Operation Enduring Freedom (OEF), and currently in Operation Inherent Resolve (OIR). The M777's lightweight design offers a more maneuverable artillery option than previous howitzers, and its use of computerized fire control systems ushered in a new era of fast and accurate artillery support.

While successful in recent combat operations, U.S. artillery is growing increasingly outmatched by adversary systems that it may face in future engagements. As it is the only cannon in the Marine Corps arsenal (United States Marine Corps, 2018), that criticism falls squarely on the M777. Congressional hearings, as well as Marine Corps guidance, allude to the growing capability gap and the need to adapt to peer[1] threats (Marine Corps Ground Modernization, 2018). In 2018, the Senate Committee on Armed Services raised these concerns during testimony on modernization efforts by the Army and the Marine Corps. In his opening comments, Chairman of the Subcommittee for Seapower, Senator Roger Wicker discussed fire support shortcomings, telling the Marine Corps Commandant, General Robert Neller, "we [Congress] expect both services [Army and Marine Corps] to work collaboratively to address shortfalls in their tube artillery and surface-to-surface missile systems" (Marine Corps Ground Modernization, 2018, p. 4). The 2016 Marine Corps Operating Concept echoes this concern of emerging threats, noting that adversaries now employ "effective ISR [intelligence, surveillance, and reconnaissance] and the ability to place long-ranged fires with precision and for massed effect" (United States Marine Corps, 2016, p. 18). Combined, these sentiments point to a growing shortfall in capability, and the need for Marine Corps artillery to adapt.

1 The term "peer" in this context refers to allied and adversary militaries that are equal in capability to that of the United States (Szayna, Bankes, & Mullins, 2001).

The M777 (see Figure 1) remains one of the superior towed artillery systems in the world. Its limitations in areas such as mobility, range, and rate of fire, however, are vulnerabilities when compared to competing systems (Bonds, 2015; Feickert, 2017; Gordon et al., 2015). Improvements in artillery technology, and a devotion to artillery-centric tactics, place adversary artillery forces in a position of considerable advantage. Employing increasingly automated systems and self-propelled platforms, adversary systems outperform the relatively rudimentary M777. The Marine Corps' ability to compete with adversary systems is complicated by the Marine Corps' expeditionary nature, and the associated need for lightweight and mobile systems.

Figure 1. M777 Lightweight Towed Howitzer. Source: Military.com (n.d.).

Compounding the shortcomings of the M777, its expected service life is scheduled to end in 2023 (United States Marine Corps, 2018), even as it now bears more responsibility than ever in the Marine Corps artillery arsenal. In 2017, the Marine Corps announced that it would no longer employ its 120 mm mortar system, the Expeditionary Fire Support System (EFSS) (Seck, 2017b; Trevithick, 2018b). This void in the arsenal places the task of artillery support for the MAGTF on either the M777 or High Mobility Rocket System (HIMARS). Neither of these systems is capable of both independent mobility and of heliborne transportability. While the M777 is capable of vertical lift, its prime mover is not, leaving it stationary upon insertion. Any subsequent moves require either further air support or delivery of its prime mover by another method. Similarly, HIMARS is too heavy for transport by vertical lift leaving its transportability limited to surface connectors or strategic airlift. These limitations mean that Marine Corps no longer possess an artillery asset capable of deploying by both air and sea connectors, while also remaining mobile immediately after landing.

Wheeled artillery presents a potential solution to this shortcoming in the Marine Corps artillery arsenal. A wheeled howitzer capable of vertical lift would provide the Marine Corps with a truly expeditionary source of fire support that is better suited for future engagements. Even if artillery systems remain restricted to deployment via surface connectors, wheeled artillery could present a more efficient, mobile, and capable platform than the M777. A global increase in wheeled artillery platforms has demonstrated this very potential and offers a solution that the Marine Corps must consider (Foss, 2008, 2014; Kemp, 2007; Valpolini, 2012). The flexibility, adaptability, and responsiveness offered by a wheeled howitzer is demonstrated through the successful incorporation of HIMARS within the Marine Corps, and a wheeled cannon would likely garner similar effects.

This analysis follows a capabilities-based assessment (CBA) framework, in order to assess if a wheeled howitzer is a suitable solution for the needs of the Marine Corps. The study mirrors the nine steps of the CBA process (see Figure 2), and ultimately compares various alternatives, and their feasibility of employment, in the future combat environment.

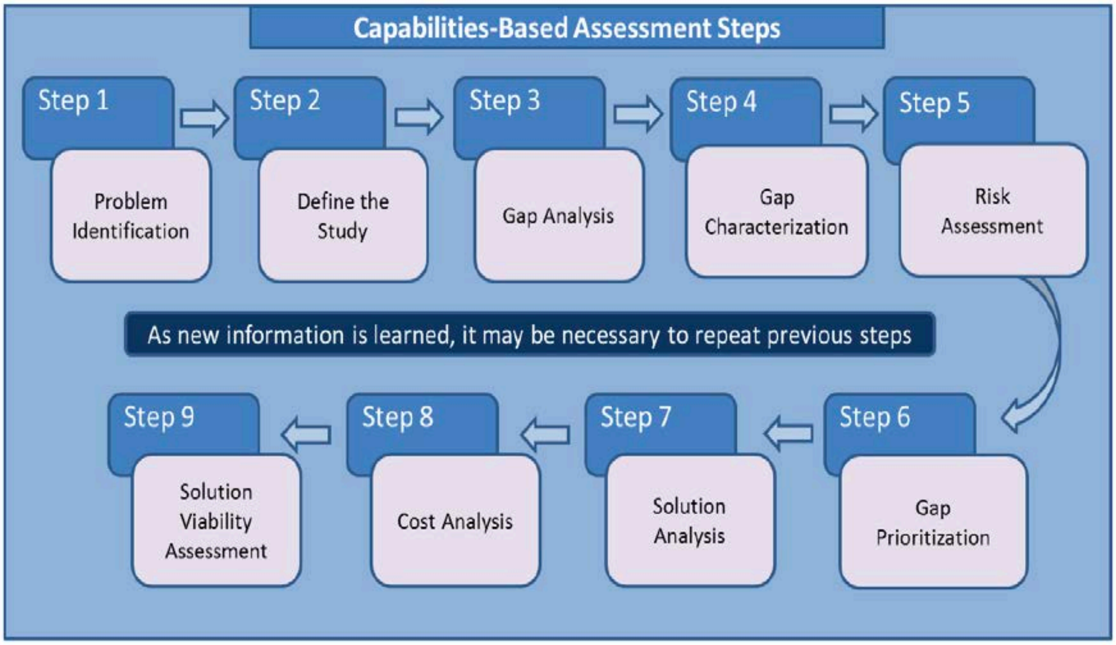

Figure 2. Capabilities-Based Assessment Steps. Source: Office of Aerospace Studies, Air Force Material Command (2014).

The study begins by discussing current force capabilities, and the current and future threats to Marine Corps artillery systems. Based upon this background, the study identifies and assesses capability gaps between Marine Corps artillery and that of peers and adversaries. The study discusses potential system requirements and tradeoffs, and selects the most relevant requirements to guide the analysis. Potential solutions are presented, discussed, and compared against one another in order to provide an analysis of alternatives.

The results of the analysis indicate that wheeled howitzers outperform towed howitzers in nearly every category. The analysis indicates that the 105 mm truck-mounted Hawkeye, in particular, provides the greatest increase in capability. Given the expeditionary nature of Marine Corps artillery, and the related requirements it imposes, the Hawkeye is well suited for inclusion in the Marine Corps arsenal. Hawkeye's rapid mobility, increased rate of fire, vertical lift capability, and ability to fit more systems on a single surface connector, makes up for its notably inferior range. Expanding the Marine Corps artillery arsenal to include the Hawkeye, or a similarly mobile wheeled howitzer, is necessary to fight and survive in the future threat environment.

II. LITERATURE REVIEW

To best evaluate the use of wheeled artillery in the Marine Corps, it is prudent to discuss the mission of Marine Corps artillery, the weapons employed, and likely future threats. There is considerable literature that discusses emerging threats, capability gaps, and global armament trends. Discussion of Marine Corps artillery, however, is largely limited to professional forums and opinion. Collectively, the various forms of existing literature orient the analysis to best address the unanswered components.

Throughout this analysis various concepts and terminology are used that are commonly understood by the artillery community. For further information on concepts and terminology see Appendix A. For insight and details beyond those in Appendix A, the following resources are recommended. Major Michael Butler's paper, *The Evolution of Marine Artillery: A History of Versatility and Relevance,* provides a comprehensive synopsis of artillery's role within the Marine Corps, including various unit histories, past technologies, and influential leaders (Butler, 2012). As much of Marine artillery overlaps with the capabilities and tactics of U.S. Army artillery, Janice McKenney's *The Organizational History of Field Artillery* is beneficial for general artillery history (McKenney, 2007). A publication by Armament Research Services, an Australian research organization, provides detailed information and analysis on artillery and indirect fire concepts (Dullum, Fulmer, Jenzen-Jones, Lincoln-Jones, & Palacio, 2017). Finally, *Marine Corps Warfighting Publication 3–16.1 Artillery Operations* is the best available resource for details on artillery tactics and employment, as well as a comprehensive glossary (United States Marine Corps, 2002).

A. THE ARTILLERY FIGHT OF TODAY AND TOMORROW

In future conflicts, the United States will inevitably face a better-equipped and more lethal opponent than the foes of past conflicts. Adversaries with large conventional militaries will foster anti-access area-denial (A2AD) environments that present a host of challenges to expeditionary operations and to artillery. This environment is far different than the counterinsurgency and anti-terror campaigns of the past decades, and as such will have different requirements. If air and sea domains are contested, naval surface fire support (NSFS) and air support's effectiveness will likely wane, emphasizing the importance of a strong artillery force (Clark & Sloman, 2016; Martin, 2017). Recent engagements around the world provide insight into the artillery fight of tomorrow, and how to best prepare for it. This evolving threat necessitates that the Marine Corps, and other services, adopt new skills and technologies accordingly.

The Russian and Chinese armies present the greatest artillery threat to the United States, and their capabilities paint a stark picture of what Marine Corps artillery could face in combat. While other nations, like Iran and North Korea, possess artillery arsenals, they are neither as technologically advanced, nor as prolific as the aforementioned Russian and Chinese systems (Feickert, 2017; Grau & Bartles, 2018). Russian and Chinese systems largely outperform Marine Corps artillery with regard to mobility, range, and rate of fire (Biass, Gander, & Gourley, 2001; Grau & Bartles, 2018), and the two nations have demonstrated a continued willingness and ability to export their artillery systems to other militaries (Feickert, 2017; Foss, 2009a; Grau & Bartles, 2018). This proliferation of artillery systems increases the likelihood that the Marine Corps will face these capabilities, even if not against Russia or China directly (Johnson, 2016). If the Marine Corps does not improve its own artillery capabilities to combat these adversary capabilities, then the likelihood of being outmatched in combat will only increase.

1. Russian Artillery

Scholars of Russian military concur that their artillery capabilities have advanced considerably in recent years. The lessons learned from the Russo-Ukrainian conflict depict these artillery advancements, demonstrating a worst-case scenario that the Marine Corps artillery must prepare to face (Fox, 2017; Grau & Bartles, 2018; Karber, 2015). A 2017 RAND study, on the lessons learned of the conflict, notes that this campaign served as a demonstration for how Russia will fight in future engagements, particularly with regard to mobility and communication (Kofman et al., 2017). Dr. Phillip Karber, of the Potomac Foundation, provides similar insight based upon his personal observations from the Russo-

Ukrainian conflict (Karber, 2015). He posits that the tactics and doctrine employed in that conflict must be considered in future U.S. military planning (Karber, 2015).

Between the summer of 2014 and winter of 2015, Russian artillery demonstrated its advanced capabilities through a series of attacks on Ukrainian forces (Karber, 2015). On July 11, 2014, the Russian Army rapidly massed artillery fires on Ukrainian forces in Zelenopillya, Ukraine, in what is regarded as the most startling of the attacks (Clem, 2017). In the attack, Russian forces fired numerous salvos of rockets on a stationary convoy of two Ukrainian mechanized battalions; the attack lasted only three minutes (Karber, 2015). In all, 23 Ukrainian soldiers were killed, 93 injured, and the convoy of vehicles destroyed (see Figure 3) (BBC News, 2014a; Karber, 2015). Additional rocket and artillery attacks occurred throughout the summer, employing a litany of artillery platforms, unmanned aerial vehicle (UAV) observation, and electronic warfare (Cranny-Evans, Cazalet, & Foss, 2018). The degree of speed and sophistication that Russia employed exemplified the standard that U.S. forces must anticipate.

Figure 3. Aftermath of the Zelenopillya Rocket Attack. Source: Woodford (2017).

The key to the Russian Army's success in the Zelenopillya attack was the speed with which they observed and attacked the convoy, proving too fast for the Ukrainians to respond. Soon after the Ukrainian convoy arrived at its position, Russian-backed hackers triangulated the convoy's position using embedded malware on the Ukrainian soldiers' cellular phone applications (Reuters, 2016). Russian tactical UAVs were then deployed, and observed the convoy (Karber, 2015). Once observed, Russian BM-21 truck-mounted rocket launchers barraged the convoy with 122 mm rockets (BBC News, 2014b; Karber, 2015). Despite being located on a road, enabling egress, the Ukrainian unit was unable to respond in time (Karber, 2015).

This sort of rapid engagement was employed throughout the Russo-Ukrainian conflict, and was not unique to Zelenopillya. Shortly after arriving at a new location, Ukrainian units would routinely observe Russian UAVs overhead, and would subsequently receive accurate artillery fire (Cranny-Evans et al., 2018). These attacks consistently occurred within a mere 10–15 minutes of Ukrainian units arriving in a position (Cranny-Evans et al., 2018). These attacks on Ukrainian forces throughout the summer of 2014 were on capable and well-equipped units, such as the 79th Airmobile Brigade in the Zelenopillya attack (Woodford, 2017). These units employ vehicles and weapons similar to those in the United States Marine Corps arsenal (Jane's by IHS Markit, 2018t), and their fate serves as a stark reminder for what U.S. forces could face on the modern battlefield.

The tactics employed by the Russian Army in the Russo-Ukrainian conflict are not new, and will likely continue into the future. Senior Army analysts, and Russian military experts, Dr. Lester Grau and Charles Bartles, note that the artillery-centric Russian army often employs a concept known as *maneuver by fire* (Grau & Bartles, 2018). This tactic masses large quantities of artillery on a key target in order to rapidly overwhelm and eliminate it (Grau & Bartles, 2018). The tactic often employs maneuver forces to encircle the enemy, effectively fixing them for destruction by artillery (Fox, 2017). This tactic is repeated on targets across the battlefield, essentially clearing the battlefield of enemy, similar to the effect of a maneuver unit. Maneuver by fire often targets other artillery units, thereby gaining fire superiority, and enabling freedom of maneuver for Russian ground forces (Grau & Bartles, 2018). The Russian Army's organization supports this tactic by providing a ratio of one artillery battalion for every maneuver battalion. It is further supported by dedicating medium-range UAVs to artillery units for observation, as was demonstrated during the 2014 and 2015 attacks on Ukrainian forces (Cranny-Evans et al., 2018; Grau & Bartles, 2018). Grau and Bartle's discussion of Russia's continued artillery and UAV modernization notes that these tactics will continue to improve over time (Grau & Bartles, 2018). Through fielding increasingly sophisticated UAV platforms and howitzers with improved firepower, Russia's artillery threat will only grow more formidable.

The Russian Army employs their artillery tactics using an increasingly advanced arsenal of cannons and rocket launchers that outperform current Marine Corps artillery capabilities. Russian self-propelled howitzers include the 2S1, 2S19, 2S3, 2S5, and 2S9, while their towed howitzers include the 2A18, 2A65, 2A19, and 2S36 (Grau & Bartles, 2018). Among these weapons, ranges can exceed 30 km, rates of fire are often over eight rounds per minute, and some systems require just 30 seconds to emplace before firing (see Table 1). The 2S35 is a new self-propelled howitzer that nearly doubles previous cannon ranges and boasts a rate of fire of 16 rounds per minute (Army-Technology, n.d.; Jane's by IHS Markit, 2018a). In addition to a litany of cannons, the Russian BM-21 Grad is a wheeled rocket-launcher that is also employed by nations like Egypt, Libya, Iran, Syria, and Yemen (Jane's by IHS Markit, 2018s). The BM-21 offers a greater range and rate of fire than the Russian cannons, and it is the very system used in the deadly Zelenopillya rocket attack (BBC News, 2014b; Jane's by IHS Markit, 2018s). As a whole, Russian artillery systems can outperform those in the Marine Corps' arsenal, particularly with regard to range, rate of fire, and mobility.

Table 1. Russian Artillery Capabilities Compared to the M777

Platform	Primary User	Type	Armament	Caliber	Max Range - GPS guided/special ammunition (m)	Max Range - Rocket assisted ammunition (m)	Max Range - unassisted ammunition (m)	Emplacement Time (sec)	Displacement Time (sec)	Rapid Rate of Fire (rds/min)	MRSI (rds)
M777A2	US Marine Corps and US Army	Towed	155 mm	39	40,000	30,000	24,700	180	120	4	-
D-30	Russia	Towed	122 mm	-	-	21,900	15,400	90	210	8	-
2S1	Russia	Tracked SP	122 mm	-	-	-	15,400	120	60	8	-
2S35	Russia	Tracked SP	152 mm	-	-	70,000	15,400	-	-	16	Yes
2S19	Russia	Tracked SP	152 mm	47	-	29,060	15,400	60-120	60-120	8	-
BM-21	Russia	Wheeled Rocket	122 mm	-	-	-	15,400	150	30	40 rds/20 sec	-

For the complete table of artillery capabilities, please see Appendix B. Areas shaded in yellow indicate capabilities greater than those of the M777. Empty boxes indicate unavailable data.

Russia's employment of maneuver by fire, dedicated UAVs for artillery observation, and a high artillery-to-maneuver ratio, were all successfully employed during the Russo-Ukrainian conflict, validating Russia's propensity for artillery attacks (Grau & Bartles, 2018; Karber, 2015). Researchers credit Russia's the improved artillery capability on these technological advancements and complimentary doctrinal changes (Grau & Bartles, 2018; Karber, 2015).

2. Chinese Artillery

While not as widely discussed as Russian artillery, Chinese artillery has also modernized considerably. A comprehensive military reorganization and numerous new artillery platforms account for China's continued modernization. In 2015, Chinese leadership began the largest military structural reform to date, ushering in an organization designed for anticipated future engagements (Cordesman, 2016). The structural reforms of the People's Liberation Army (PLA) are intended to allow China to conduct multiple simultaneous land wars (Cordesman, 2016; Engstrom, 2018). Despite the massive reorganization and modernization efforts, China believes it is still far from its objective, and therefore continues its aggressive advancement efforts (Cordesman, 2016).

The reform's sweeping changes include the distribution of command and technological advancements within the PLA. Chinese leadership emphasized the importance of mobility, prompting the production of new weapon systems, and the execution of numerous large exercises (Cordesman, 2016). Among the focal points of the PLA's modernization is the continued fielding of tracked and wheeled artillery (Cordesman, 2016; Foss, 2009a). By incorporating mobile, long-range artillery systems, China seeks to establish a component of its desired strike capability (Cordesman, 2016).

In order to aid in these modernization efforts, China recently developed and fielded numerous new artillery platforms. Chinese manufacturer, NORINCO developed many of the weapons for the PLA, and offers most of them for export as well (Foss, 2009a). Among the new highly-mobile platforms are the tracked PLZ45, SH3, and PLZ52, and the wheeled SH1, SH2, and SH4 (Foss, 2009a). The towed AH1 and AH2 cannons, and the SH4 rocket launcher are also part of the wide array of artillery assets (Foss, 2009a). All of these systems possess capabilities comparable to Russian systems, and in many cases, exceed those of Marine Corps systems (see Table 2). Leveraging both Russian and NATO caliber ammunition, Chinese artillery systems span the spectrum of capabilities, creating another formidable artillery opponent for the Marine Corps (Foss, 2009a).

Table 2. Chinese Artillery Capabilities Compared to the M777

Platform	Primary User	Type	Armament	Caliber	Max Range - GPS guided/special ammunition (m)	Max Range - Rocket assisted ammunition (m)	Max Range - unassisted ammunition (m)	Emplacement Time (sec)	Displacement Time (sec)	Rapid Rate of Fire (rds/min)	MRSI (rds)
M777A2	US Marine Corps and US Army	Towed	155 mm	39	40,000	30,000	24,700	180	120	4	-
NORINCO SH1	China	Wheeled SP	155 mm	52	-	53,000	32,000	-	-	-	-
NORINCO SH2	China	Wheeled SP	122 mm	-	-	27,000	15,300	-	-	-	-
NORINCO SH3	China	Tracked SP	122 mm	-	-	27,000	17,000	-	-	-	-
NORINCO SH4	China	Wheeled Rocket	122 mm	-	-	27,000	15,300	-	-	-	-
NORINCO SR4	China	Wheeled Rocket	122 mm	-	-	50,000	30,000	300	30	40 rds/30 sec	-
PLZ45	China	Tracked SP	155 mm	45	-	50,000	39,000	-	-	5	-
PLZ52	China	Tracked SP	155 mm	52	-	58,000	-	-	-	8	4

For the complete table of artillery capabilities, please see Appendix B. Areas shaded in yellow indicate capabilities greater than those of the M777. Empty boxes indicate unavailable data.

China's doctrine has also developed, demonstrating the growing importance of fire support to the Chinese military. China implemented a system known as the *firepower strike system*, which is a network of various fire support assets intended to collectively destroy the enemy and deny access to the region (Engstrom, 2018). The PLA's modernized long-range artillery provides the land-based component of this larger fires network (Engstrom, 2018). While long-range fire support capability is generally achieved through missile systems provided by the PLA Rocket Force, traditional cannon and rocket artillery is growing increasingly relevant, and would likely serve a critical role in the event of numerous concurrent engagements (Foss, 2009a). This combination of modern technology and complimentary doctrine makes Chinese artillery a considerable threat to the United States Marine Corps.

B. UNITED STATES MARINE CORPS ARTILLERY

> The mission of artillery is to furnish close and continuous fire support by neutralizing, destroying or suppressing targets that threaten the success of the supported unit. (United States Marine Corps, 2002)

In accordance with its mission, Marine Corps artillery must remain capable of supporting the advancing needs of the Marine Corps as a whole. Artillery is called upon to provide fast, accurate, and effective fire support capabilities, provide a counterfire capability to the ground force, and deliver depth of force to shape the battlespace (United States Marine Corps, 2002). This task requires continued advancements in tactics and technology in order to match evolving threats to the MAGTF; otherwise the Marine Corps' lethality will wane to future opponents.

Nested beneath the guiding principles of the National Security Strategy and the National Defense Strategy, the 2016 Marine Corps Operating Concept, provides the foundational guidance for how the Marine Corps, and Marine Corps artillery, must operate and develop in the coming decades (United States Marine Corps, 2016). The central notion of the guidance is that the Marine Corps must prepare and train to fight in an increasingly complex and contested battlespace, for which it is currently unprepared (United States Marine Corps, 2016). Specific to fire support, the Marine Corps Operating Concept notes that future adversaries will have considerable ISR capabilities that enable the use of both precision and massed fires (United States Marine Corps, 2016). Due to this persistent threat, there is a pertinent need for artillery to be capable of "conducting rapid counter-battery and defensive fires" and of "engaging in quick-response offensive fires mission" (United States Marine Corps, 2016, p. 18). This capability requires "rapidly mobile fire systems" that can operate "within and outside complex terrain, including urban areas" (United States Marine Corps, 2016, p. 18). In order to achieve this, the Marine Corps Operating Concept goes on to suggest the need to "develop fire support systems [that provide] the range, precision, and agility to survive against peer fires systems" (United States Marine Corps, 2016, p. 22).

The ability to meet the Marine Corps Operating Concept's expectations is complicated by the variety of expeditionary missions that Marine Corps artillery may face. Recent Marine artillery employment has ranged from supporting maneuver forces to defending from a fire base, inspiring disparate system requirements. This need to prepare for a broad set of requirements makes selecting a single artillery system a considerable challenge.

The need for rapidly mobile artillery to support fast-moving maneuver units was put to the test in 1991 in Operation Desert Storm and again in Operation Iraqi Freedom (OIF) in 2003. In his publication, *Artillery Strong*, U.S. Field Artillery School Historian, Dr. Boyd Dastrup expresses that Desert Storm proved artillery's ability to support fast-moving maneuver units, contrary to its many skeptics (Dastrup, 2018). Some, however, observed that the M198 towed howitzer occasionally fell behind the maneuver units it supported, primarily due to its slow displacement times, raising concerns of its effectiveness (Dastrup, 2018). These same concerns continued leading up to OIF, but were dismissed as artillery proved capable of supporting fast-moving tank, light armored reconnaissance (LAR), and mechanized infantry units (Field, 2004).

While Desert Storm and OIF exemplified a more traditional application of artillery support, Operation Enduring Freedom (OEF) employed artillery in a less traditional role. During the 2001 amphibious assault into Afghanistan, the 15th Marine Expeditionary Unit (MEU)'s artillery was not included (Lowery, 2011). Instead it was left on the ship, as the large amount of space it consumed was better spent transporting other forces (Lowery, 2011). Eventually, Marine artillery did deploy to Afghanistan where it was often placed into semi-permanent fire bases, where it provided offensive and defensive fire support for operations occurring within range of that fire base (Kummer, 2014; Potomac Defense Daily, 2009). While primarily employed in this capacity, the mission occasionally called for mobile artillery support through rugged terrain, complicating the requirements of artillery support (Kummer, 2014). This variety of roles called for an array of capabilities, such as precision munitions and lightweight cannons capable of operating in mountainous terrain.

Similar to artillery use in OEF, Operation Inherent Resolve (OIR) demonstrated another example of artillery use in the fire base capacity. In 2016, the 26th MEU's artillery battery was tasked with establishing a fire base in support of coalition operations against the Islamic State (Gordon, 2017). As described by the MEU's Ground Combat Element (GCE) Commander in *The Marine Corps Gazette*, this was the first instance where artillery took on the primary mission of the MEU (Gordon, 2017). To support operations, four towed M777A2s were inserted via strategic lift, established an austere firebase, and provided counterbattery fires and offensive fire support for the Iraqi army (Gordon, 2017). A similar mission was conducted in Syria in 2017 by another Marine artillery battery, this time from the 11th MEU (Cox, 2018). These recent examples of Marine artillery employment exemplify the continued need for rapidly deployable, survivable, and capable fire support systems.

1. Artillery Systems

To aid in fulfilling the wide array of artillery missions, the Marine Corps employed a concept that became known as the fire support triad. This triad consisted of three, land-based, indirect fire platforms, and was fielded in its entirety in 2009 (United States Marine Corps, 2010). The triad included the M777, the M142 HIMARS, and the M327 EFSS (Jane's by IHS Markit, 2017d; United States Marine Corps, 2010). Combined, the triad's systems could support missions between 100 m and 70 km, and offered a variety of weaponeering options (Jane's by IHS Markit, 2017d, 2018n). This triad concept ultimately enabled Marine artillery to support the MAGTF across a large battlespace, with the most appropriate weapon for the given environment.

a. M777

The primary system of this triad is the towed 155 mm/39-caliber M777, which is currently fielded in nine of the 11 Marine Corps artillery battalions (United States Marine Corps, 2018). The M777A2 employs enhanced digital capabilities, and is the currently fielded variant of the M777 family. The M777's lightweight 10,000 lbs. design is intended for lift by the CH-53E/K and the MV-22, aiding in its improved mobility and transportability over its heavier predecessor, the M198 (United States Marine Corps, 2018). The weight was of such importance that it was one of key performance parameters (KPP) for the system, along with the requirement of a three-minute emplacement time, and a two-minute displacement time (Report on Utilization of Rock Island Arsenal, 1999). Its towed design eliminated the increased maintenance requirements associated with tracked or motorized platforms, thereby offering more consistent employment (Dullum et al., 2017; Turbé, 2010). The tradeoff is the M777's reliance on its prime mover, the Medium Tactical Vehicle Replacement (MTVR), for towing and power generation (Jane's by IHS Markit, 2018o). With six cannons in each firing battery, and three firing batteries per battalion, the M777 provides the bulk of the Marine Corps' indirect firepower.

b. HIMARS

The M142 HIMARS rocket launcher is another component of the triad, and provides long-range fire support to the MAGTF. HIMARS consists of an interchangeable rocket pod affixed to a six-wheeled truck chassis (Jane's by IHS Markit, 2018n). The Marine Corps currently has one reserve HIMARS battalion, and one active battalion with a second battalion activating in 2019 (United States Marine Corps, 2018). The M142 is capable of firing both Guided Multiple Launch Rocket System (GMLRS) and Army Tactical Missile System (ATACMS) rockets (Jane's by IHS Markit, 2018n). GMLRS is a set of six GPS-guided rockets, and is the more common ammunition, offering a range in excess of 70 km (Jane's by IHS Markit, 2018n). The less common ATACMS is a large unitary rocket, capable of firing nearly 300 km and is less commonly employed (Jane's by

IHS Markit, 2006). After firing the contents of either type of rocket pod, the launcher is reloaded with a new pod by one of its two accompanying ammunition vehicles (Jane's by IHS Markit, 2018n). In October 2017, a HIMARS launcher successfully struck land targets, firing from the back of a U.S. Navy amphibious ship (United States Naval Institute, 2017). This emerging capability to fire onboard a ship offers the potential to augment NSFS during amphibious operations, aiding in an A2AD environment and compounding its value to the Navy and Marine Corps (Bonds et al., 2017).

c. Expeditionary Fire Support System

From 2009 to December 2017, the Marine Corps also employed the Expeditionary Fire Support System (EFSS) as the third system of the fire support triad (Jane's by IHS Markit, 2017d). The EFSS consisted of the M327, 120 mm rifled mortar system (see Figure 4), and a small, dedicated truck as its prime mover. The system was designed for transport inside the Marine Corps' MV-22, making the system capable of vertical lift and immediately mobile after landing (Jane's by IHS Markit, 2017d). This ability to fit inside of the MV-22 made the EFSS a desirable system for airborne assaults and raids. With limited means of ship-to-shore transit, this capability offered a valuable method option for echeloning fire support systems ashore (United States Marine Corps, 2010). The requirement to internally carry the entire EFSS system, however, created constraints on the system's design, as indicated in a 2008 Government Accountability Office (GAO) report (Government Accountability Office, 2008). The GAO report found that the EFSS was unable to securely carry all of its necessary equipment, raising concerns about its safety and effective utility (Government Accountability Office, 2008). The EFSS did, however, successfully deploy in support of OEF in 2011, proving some utility to the Marine Corps (Lowe, 2011).

In December of 2017, the Marine Corps announced that the EFSS would no longer be fielded in the operational force (Seck, 2017b; Trevithick, 2018b). While one of EFSS's primary features was its ability to embark and disembark from the MV-22 rapidly, this task was in fact considered difficult and burdensome (Trevithick, 2018b). Additionally, the M1163 truck used to tow it had a lengthy history of maintenance issues and survivability concerns (Government Accountability Office, 2008). Unable to conduct direct fire, and with a maximum range of only 13 km, the EFSS no longer aligned with the anticipated future threat environment (Jane's by IHS Markit, 2017d).

Figure 4. Expeditionary Fire Support System.
Source: Foss (2018).

d. Future Marine Artillery Systems

Shortly after the EFSS's removal from service, the Marine Corps demonstrated an interest in other lightweight and compact artillery platforms. In September 2017, a 105 mm cannon mounted on a High Mobility Multipurpose Wheeled Vehicle (HMMWV), known as the Hawkeye (see Figure 5), drew the attention of Marine Corps leadership at the Modern Day Marine 2017 symposium (Cox, 2017). The system, developed by Mandus Group, employs soft recoil technology facilitating a lightweight design (Cox, 2017). In October 2017, the Marine Corps also expressed an interest in developing an air-mobile version of the HIMARS launcher, capable of being mounted on a mobile vehicle such as a HMMWV or Joint Light Tactical Vehicle (JLTV) (Seck, 2017a). Both of these potential systems provide an artillery platform capable of vertical airlift that is also independently mobile after landing, a capability lost with the retirement of the EFSS.

Figure 5. Hawkeye. Source: Mandus Group (2016).

2. Assessment of Marine Corps Artillery

Unfortunately, assessments of Marine Corps artillery is rarely discussed outside of the community. Receiving less scholarly attention than other military capabilities, the forum for these discussions is largely left to publications such as *Fires* and *The Marine Corps Gazette*. While not necessarily research-based, these forums provide professional opinions, often supported by anecdotal evidence. Nevertheless, the expertise of artillery leadership and the Marine Corps community at large provides insight into the effectiveness of U.S. artillery, and the potential for wheeled artillery.

Many articles by those within the artillery community point to the past successes of Marine artillery's fire support triad, particularly the M777 and HIMARS (Johnson, Mogenson, Peery, Fears, & Tate, 2011; Mogenson & Tate, 2013; Pace, 2005). These proponents argue that possessing a scalable artillery force, capable of tailoring itself to the needs of the MAGTF, is incredibly beneficial. The relative lighter weights of the M777 and EFSS were considered to align with the expeditionary needs of the Marine Corps, while HIMARS provided the longer range support (Johnson et al., 2011; Mogenson & Tate, 2013; Pace, 2005). Combined with advancing ammunitions for each system, the combination of systems successfully covered the MAGTF's requirements.

Discussion among the community mostly praised the M777, especially in the years following its inception. Even today, the M777 receives accolades from users and leaders for its versatility and effectiveness (Gordon, 2017; Potomac Defense Daily, 2009). Supporters point to the M777's lighter and more maneuverable design when compared to its predecessor the M198 (Hoerster & Boulet, 2004; Johnson et al., 2011; Pace, 2005). Most important of all is the M777's repeated performance in combat in a variety of environments (Gordon, 2017; Kummer, 2014; Potomac Defense Daily, 2009). Broader support of towed artillery also points to historical successes in urban operations, support of fast-moving units, and counterbattery and firebase operations, despite critics (Field, 2004; Gordon, 2017).

Despite considerable support of the M777 others note its relative inferiority to peer artillery systems as unacceptable. At its introduction, criticism originally centered on how little the M777 advanced from the M198's, capabilities (Clark, 2003; Lankford, 2000). Even prior to the M777's introduction, competing howitzers outperformed it in range, rate of fire, and emplacement and displacement times (Lankford, 2000; Sadler, 2000). The M777, however, was not compared to these competing systems, rather its comparison was limited to its predecessor, M198 (Hoerster & Boulet, 2004; Lankford, 2000; Pace, 2005; Potomac Defense Daily, 2009; Sadler, 2000). Among the greatest criticisms was the M777's reliance on its large prime mover (Clark, 2003; Gannon, 2013; Lankford, 2000). While the M777 itself was lighter and more capable than the M198, it still required the dedication of a cumbersome truck in order to move, giving it similar constraints in employment to the M198. If the M777 was supposed to merely be an improvement from the M198, then there is consensus that it succeeded (Hoerster & Boulet, 2004; Pace, 2005). If the M777, along with its prime mover, was supposed to compete with capabilities of other peer systems in the global arsenal, then the M777 failed from the onset.

Much of the M777's support is based on its successes in past wars, and in its relative improvement in capability over its predecessor. Instead its success and value should be assessed on its ability to fight in future engagements.

C. DEFINING THE ARTILLERY CAPABILITY GAP

Throughout the artillery and military communities, the growing threat of adversary artillery is largely uncontested. Growing arsenals, advancing technology, and revised doctrine demonstrate a commitment and emphasis on artillery in future engagements. Aggressive adversary advancements in artillery yield a widening capability gap in comparison to U.S. capabilities (Feickert, 2017; Gordon et al., 2015). Identifying the scope of this capability gap is admittedly complicated since observable interactions between two opposing sides only occur during actual combat. Short of acquiring and testing each system, or observing a future conflict, analysts are left to conduct historical, numerical, and doctrinal analyses. Additionally, various military and proprietary classifications complicate the ability to accurately compare system capabilities. Given these constraints, it is difficult to identify the exact role that wheeled artillery will serve in overcoming the capability gap. Conducting an educated and objective analysis still remains the most effective method in defining the capability gap.

Multiple studies describe the emergence of capability gaps between the United States and its foes, based on comparative analyses. The research attributes the widening gap in artillery capabilities to a combination of foreign advancement and American stagnation. In studies by both RAND and the Congressional Research Service, researchers suggest that U.S. ground combat vehicles, to include artillery systems, are outperformed by those of adversaries, specifically to Russian systems (Feickert, 2017; Gordon et al., 2015). The studies also find many allied capabilities surpassing those of the U.S. (Feickert, 2017; Gordon et al., 2015). While these studies largely focus on the U.S. Army's capabilities, many of these systems and capabilities are common to the Marine Corps, allowing for the extension of these conclusions. Among the literature, the commonly identified shortcomings can be categorized into one of three capability gaps: firepower, mobility, and transportability.

1. Firepower

The firepower gap is the most notable of the three capability gaps. The gap has been identified and discussed by researchers, scholars, military decision makers, and even

Congress. In a series of studies by the RAND Corporation, the M777 and the U.S Army's M109 were identified as notably inferior in range and rate of fire to allied and adversary systems (Gordon et al., 2015; Johnson, 2016). While the study confirmed that the M777 is a capable towed system, its authors recommend improvements in "mobility, responsiveness, and rate of fire" despite "inevitably add[ing] weight and complexity to the system" (Gordon et al., 2015, p. 33). These studies unwaveringly suggest the need for a long-range counterfire capability (Gordon et al., 2015; Johnson, 2016).

These sentiments were echoed in a 2017 Congressional Research Service (CRS) report, which identified a combination of increased adversary artillery capabilities and a reduced U.S. artillery force as the source of the gap (Feickert, 2017). Among the identified shortcomings of U.S. artillery were range, rate of fire, and ammunition. The report notes the following.

> The dichotomy of diminished U.S. artillery capability—based on fewer units, pending limitations on cluster munitions, and shorter effective ranges—versus potential protagonists who possess longer range systems, a wider variety of munitions, and who are employing innovative target acquisition techniques presents potentially significant challenges for the U.S. Army. (Feickert, 2017, p. 19)

Also citing the Russo-Ukrainian conflict as a source of concern, the report clearly suggests the need for improvement of U.S. artillery systems (Feickert, 2017).

In addition to the reports and studies, a numerical comparison between U.S., adversary, and allied systems depicts the various disparities. Combined these shortcomings are proof of a larger firepower capability gap, and the conclusion that U.S. artillery is in a position of disadvantage (Biass et al., 2001; Goure, 2016). In nearly every characteristic, the M777's firepower is out performed by other systems (see Table 3).

Table 3. Worldwide Howitzer Firepower Capabilities

Platform	Primary User	Type	Armament	Caliber	Max Range - GPS guided/special ammunition (m)	Max Range - Rocket assisted ammunition (m)	Max Range - unassisted ammunition (m)	Emplacement Time (sec)	Displacement Time (sec)	Rapid Rate of Fire (rds/min)	Susustained Rate of Fire (rds/min)	MRSI (rds)
M777A2	US Marine Corps and US Army	Towed	155 mm	39	40,000	30,000	24,700	180	120	4	2	-
AS-90	UK	Tracked SP	155 mm	39	-	-	30,000	-	-	6	2	-
PzH2000	Germany	Tracked SP	155 mm	52	56,000	40,000	30,000	-	-	3 rds/9 sec	10	5
ATMOS 2000	Israel	Wheeled SP	155 mm	52	-	-	41,000	60	60	9	4	-
G-6	South Africa	Wheeled SP	155 mm	45	38,000	53,600	31,000	60	30	3	2	-
ARCHER	Sweden	Wheeled SP	155 mm	52	50,000	-	40,000	20	20	9 rds/min 3 rds/20sec	-	6
CAESAR	France	Wheeled SP	155 mm	52	-	58,000	30,000	35	30	3 rds/15 sec	6	-
K9 Thunder	South Korea	Tracked SP	155 mm	52	-	30,000	18,000	60	-	8	3	-
EVO-105	South Korea	Wheeled SP	105 mm	34	-	18,000	14,700	-	-	10	3	-
Tasko	Ukraine	Wheeled SP	155 mm	52	-	-	42,000	60	60	3 rds/15 sec	-	-
D-30	Russia	Towed	122 mm	-	-	21,900	15,400	90	210	8	-	-
2S1	Russia	Tracked SP	122 mm	-	-	-	15,400	120	60	8	-	-
2S35	Russia	Tracked SP	152 mm	-	-	70,000	40,000			16	-	Yes
2S19	Russia	Tracked SP	152 mm	47	-	29,060	24,700	60-120	60-120	8	-	-
BM-21	Russia	Wheeled Rocket	122 mm	-	-	-	-	150	30	40 rds/20 sec	-	-
NORINCO SH1	China	Wheeled SP	155 mm	52	-	53,000	32,000	-	-	-	-	-
NORINCO SH2	China	Wheeled SP	122 mm	-	-	27,000	15,300	-	-	-	-	-
NORINCO SH3	China	Tracked SP	122 mm	-	-	27,000	17,000	-	-	-	-	-
NORINCO SH4	China	Wheeled Rocket	122 mm	-	-	27,000	15,300	-	-	-	-	-
NORINCO SR4	China	Wheeled Rocket	122 mm	-	-	50,000	30,000	300	30	40 rds/30 sec	-	-
PLZ45	China	Tracked SP	155 mm	45	-	50,000	39,000	-	-	5	-	-
PLZ52	China	Tracked SP	155 mm	52	-	58,000	-	-	-	8	-	4

For the complete table of artillery capabilities, please see Appendix B. Areas shaded in yellow indicate capabilities greater than those of the M777. Empty boxes indicate unavailable data.

As suggested by the various reports, there is indeed an identifiable gap in firepower capabilities between U.S. artillery, and that of other militaries. The studies admittedly focus primarily on equipment capabilities, and omit other factors such as training and manning (Gordon et al., 2015). Rate of fire, on the M777 for example, can be partially improved upon through training. A system's physical capabilities, however, place a limit on the extent that training alone can improve. Ultimately, the gap of physical system characteristics is too great to be overcome by non-material means alone.

2. Mobility

Another notable capability gap is the mobility of current systems. The need for improved mobility is noted in a CRS report, Army analyst Douglas Macgregor's book *Breaking the Phalanx,* as well as various and papers (Dullum et al., 2017; Feickert, 2017; Harris, 2017; Macgregor, 1997). Mobility is also discussed throughout the Marine Corps Operating Concept, as it is anticipated to be a critical component of future engagements (United States Marine Corps, 2016). The need to move rapidly and effectively around the battlefield is imperative, particularly when facing a responsive and capable adversary.

The comparative military study, conducted by RAND, identified U.S. artillery mobility as notably deficient (Gordon et al., 2015). This was echoed by CRS's 2017 evaluation (Feickert, 2017). In an environment with increasingly lethal and responsive threats, the ability to move and respond rapidly is paramount. Macgregor has long advocated the importance of a mobile and adaptable force, as opposed to a large reinforced force (Macgregor, 1997). Macgregor emphasizes the importance of "dispersed, highly mobile ground forces" (Macgregor, 1997, p. 127) when fighting advanced adversaries, such as Russia and China. As such, he encourages the Army, and the Marine Corps, to adopt this smaller and more mobile approach.

When compared to other artillery systems, the M777 fails to achieve the mobility that experts suggest is required in the future. While its transit speed is comparable to other platforms, and the cannon's light weight is conducive to mobility, the time required to emplace and displace presents a considerable vulnerability (see Table 4). This need for a rapid emplacement and displacement capability is discussed in the 2016 Naval Postgraduate School thesis on artillery survivability, by Yusuf Temiz (Temiz, 2016). Among the analysis' outputs was the importance of speed and mobility for a howitzer's survival (Temiz, 2016).

Table 4. Worldwide Howitzer Mobility Capabilities

Platform	Primary User	Type	Emplacement Time (sec)	Displacement Time (sec)	Road Speed (MPH)	Combat Load (Rounds)	Crew Size	Crew Fires From Cover	Armor	Driving Range (miles)
M777A2	US Marine Corps and US Army	Towed	180	120	55	No	7	-	-	-
M777A2 with MTVR	US Marine Corps	Towed	180	120 sec	60	No	7	-	-	300
M109A7	US Army	Tracked SP	60	120	38	-	4	Yes	Yes	186
AS-90	UK	Tracked SP	-	-	34	48	5	Yes	Yes	230
PzH2000	Germany	Tracked SP	-	-	37	60	5	Yes	Yes	261
ATMOS 2000	Israel	Wheeled SP	60	60	50	27	6	Yes	Yes	621
G-6	South Africa	Wheeled SP	60	30	53	45	6	Yes	Yes	435
ARCHER	Sweden	Wheeled SP	20	20	43	21	3	Yes	Yes	311
CAESAR	France	Wheeled SP	35	30	62	18	4	-	-	373
K9 Thunder	South Korea	Tracked SP	60	-	62	48	5	Yes	Yes	224
EVO-105	South Korea	Wheeled SP	-	-	53	60	5	Partial	-	-
Tasko	Ukraine	Wheeled SP	60	60	-	16	-	-	-	-
D-30	Russia	Towed	90	210	50	-	7	-	Yes	-
2S1	Russia	Tracked SP	120	60	37	40	4	-	-	311
2S35	Russia	Tracked SP	-	-	40	70	3	-	-	372
2S19	Russia	Tracked SP	60-120	60-120	37	50	5	-	-	280
BM-21	Russia	Wheeled Rocket	150	30	53	40	6	-	-	646
NORINCO SH1	China	Wheeled SP	-	-	56	20	6	Yes	Yes	-
NORINCO SH2	China	Wheeled SP	-	-	56	24	5	Yes	Yes	372
NORINCO SH3	China	Tracked SP	-	-	37	40	5	Yes	Yes	311
NORINCO SH4	China	Wheeled Rocket	-	-	-	-	-	-	-	-
NORINCO SR4	China	Wheeled Rocket	300	30	-	40	-	-	-	-
PLZ45	China	Tracked SP	-	-	34	30	5	Yes	Yes	-
PLZ52	China	Tracked SP	-	-	40	30	4	Yes	Yes	280

For the complete table of artillery capabilities, please see Appendix B. Areas shaded in yellow indicate capabilities greater than those of the M777. Empty boxes indicate unavailable data.

Much of the M777's mobility concerns are not exclusive to that one system, but rather are challenges of all towed artillery. With slower displacement and emplacement times than self-propelled counterparts, the M777 is at a numerical disadvantage when its mobility includes these considerations. Due to the towed nature, employment requires manual involvement and maneuvering the truck and howitzer, which is a labor-intensive and time-consuming endeavor. While this process has not kept the M198 and M777 from supporting fast-moving maneuver units in past engagements, towed howitzers are outmatched when faced with the rapid and capable threats of tomorrow.

3. Transportability

Transportability is the most difficult capability to define, and it presents the greatest capability tradeoff. Transportability, as it pertains to Marine Corps artillery, generally speaks to the ability to move from ship to shore. Amphibious landings are a staple of Marine Corps doctrine and capabilities, and Marine forces must therefore be transportable by various ship-to-shore means (United States Marine Corps, 2016). MEUs possess landing craft air cushions (LCACs) and landing craft utilities (LCUs) to transport personnel and equipment ashore by sea, while CH-53E/Ks and MV-22s provide transport by air (Congresisonal Budget Office, 2016). Ideally, any system in the Marine Corps arsenal would be capable of transport by all of these ship-to-shore connectors, thus enabling the greatest number of options for amphibious operations (Department of the Navy, 2011). This, however, is complicated as systems grow larger, heavier, and more complex.

Despite the claims, the M777 is not truly able to achieve this goal of transport by all ship-to-shore connectors. The M777's dependence on its prime mover, the MTVR, restricts either functionality or transportability of the system (Clark, 2003; Gannon, 2013; Lankford, 2000). Only the cannon is capable of insertion by MEU aircraft, making its full functionality dependent on surface connectors, or strategic airlift, delivering the prime mover (see Figure 6). This was the case in its employment in OIR, where the M777 was deployed by Air Force C-17 strategic lift (Gordon, 2017). Availability of strategic airlift is unlikely to be available in a future contested environment (Clark & Sloman, 2016). When left to only the MEU's organic means of transport ashore, the M777's transportability limitations remain.

Top left: M777 and MTVR on LCAC. Source: Contreras (2013). Top Right: M777 and MTVR on LCU. Source: Military Mashup (n.d.). Bottom Left: M777 lifted by CH-53. Source: Military.com (n.d.). Bottom Right: M777 and MTVR on LCU. Source: Navy Supply Corps Newsletter. (2014).

Figure 6. M777 Transportability.

The M777's towed concept, and reliance on a large prime mover, creates a gap in capabilities of the Marine Corps' arsenal. With the retirement of the EFSS, the Marine artillery community no longer possesses a single system that can fully perform all of its functions when supported by MEU aircraft alone. This transportation restriction means that cannons must rely at least partially on surface connectors for transport to shore. Remaining stationary upon landing and being restricted to surface connectors are both unacceptable in future contested amphibious operations (Clark & Sloman, 2016).

System transportability is most directly related to the size and the weight of the system. Many of the world's cannons that outperform the M777 in range, rate of fire, and mobility, do so at the expense of their transportability (Foss, 2003; Valpolini, 2012). These systems often possess large footprints and heavy weights in order to achieve these capabilities (see Table 5). While their firepower may be ideal for combatting future foes, their size prohibits the use of airlift, and restricts flexibility in amphibious operations.

Table 5. Worldwide Howitzer Transportability

Platform	Primary User	Type	Weight (lbs)	Transport Length (in)	Transport Width (in)	Transport Height (in)
M777A2	US Marine Corps and US Army	Towed	9,100	385.2	101.9	105.8
M777A2 with MTVR	US Marine Corps	Towed	37,000	701.2	101.9	140
M109A7	US Army	Tracked SP	80,000	382	154	129
AS-90	UK	Tracked SP	99,208	389.8	133.9	118.1
PzH2000	Germany	Tracked SP	121,981	459.4	140.9	136.2
ATMOS 2000	Israel	Wheeled SP	46,297	374	98.4	-
G-6	South Africa	Wheeled SP	103,617	406.9	133.9	149.6
ARCHER	Sweden	Wheeled SP	74,957	563	118.1	129.9
CAESAR	France	Wheeled SP	39,021	391.3	100.4	106.3
K9 Thunder	South Korea	Tracked SP	102,074	472.4	133.9	137.8

For the complete table of artillery capabilities, please see Appendix B.

Transportability capabilities are largely contingent on if a vertical lift capability is a critical requirement. If a vertical lift capability is not required, then the system is less restricted by transportability and the Marine Corps could elect any system with greater automation and more armor, regardless of size or weight. Requiring that a system be capable, or partially capable, of vertical lift imposes considerable restrictions on the potential systems. In the case of the M777, while the cannon is capable of transport by vertical lift, it is unfair to consider the system fully functional without its prime mover (Clark, 2003; del Mazo & Giorgis, 2018). Maintaining the M777’s transportability capability comes at the expense of other capabilities it could otherwise include.

D. THE WORLDWIDE TREND TOWARD WHEELED ARTILLERY

In recent years many nations have opted to develop and acquire wheeled self-propelled howitzers, vice heavier and more expensive tracked platforms (Foss, 2014). A primary reason for this shift is the ease of mobility and transportability offered by wheeled platforms (Valpolini, 2012). Technical requirements, such as lighter weights and transport by C-130, limits options to either towed or wheeled platforms (Foss, 2003; Valpolini, 2012). These sorts of imposed restrictions are a reason for much of this shift.

Another technical advantage of a wheeled system is the cheaper cost to maintain (Valpolini, 2012). In 2017, the RAND Corporation conducted a historical comparison of tracked and wheeled vehicles for the Australian military (Matsumura et al., 2017). Among the study's findings was that wheeled vehicles, across the board, have lower operations and maintenance costs than their tracked counterparts (Matsumura et al., 2017). Considering financial constraints that many militaries face, this mobile and cost-saving solution offers an appealing alternative.

To feed this recent appetite for wheeled systems, defense manufacturers are creating new wheeled howitzers, and are converting and improving existing howitzers into wheeled ones. The French CAESAR was first fielded in 1994 and it remains a leading wheeled system, having tested its combat capabilities in Afghanistan and Mali (Foss, 2014). Its manufacturer, NEXTER, successfully sells the platform internationally as-is, but has recently offered to mount the cannon on any truck platform, in an attempt encourage new customers with different vehicle fleets (Jane's by IHS Markit, 2018p). A similar concept is offered by German manufacturer Krauss Maffei Wegmann (KMW), who offers to place their artillery gun module (AGM) from their German PzH2000 on any platform that the customer desires, wheeled or tracked (Foss, 2014). Israel's ATMOS 2000 and the Swedish ARCHER are among the newer, purpose-built wheeled howitzers on the market (BAE Systems International, n.d.; Jane's by IHS Markit, 2018d).

This recent shift to wheeled howitzers is not limited just to the United States' allies. China's NORINCO has recently made the SH1 and SH2, two varieties of wheeled howitzer, as well as the SH4, a wheeled rocket launcher (Foss, 2014). Militaries and manufacturers around the world are noting the advantages of wheeled artillery, and are changing their arsenals accordingly.

E. WHEELED HOWITZERS IN MARINE CORPS

Given the changing threat environment, the Marine Corps has seemingly come to the realization that change is needed within its artillery community, and a wheeled cannon may present the solution. Recent interest in new mobile systems aligns with guidance published in the Marine Corps Operating Concept (Cox, 2017; United States Marine Corps, 2016). As explained in the Marine Corps Operating Concept, MAGTFs must seek to “employ units with a smaller size and footprint” (United States Marine Corps, 2016, p. 16). A large and heavy tracked platform directly defies that guidance. If the Marine Corps adopts a self-propelled artillery system, it would almost certainly be wheeled, as the size, weight, and costs associated with wheeled systems are better aligned with the Marine Corps’ mission than a tracked howitzer. The Marine Corps previously employed the M109, tracked howitzer, but replaced it with systems more compatible with expeditionary operations (Butler, 2012).

The Marine Corps has begun to consider whether the worldwide trend towards wheeled howitzers is a viable option for the Marine Corps pursue (C. Hatch, email to author, September 18, 2018). The Program Manager for Towed Artillery Systems (PM-TAS) office provided insight on this discussion, identifying four potential courses of actions for the future of Marine cannon artillery, specifically with regard to the M777 and its eventual replacement.

1. M777 SLEP

One alternative is to continue to use and improve the M777, while accepting its current limitations. The M777’s estimated life cycle is currently scheduled to end in 2023 (United States Marine Corps, 2018), but a service life extension program (SLEP) could extend its service life beyond that date. Additional improvements and modifications could continue with this alternative, such as the application of chrome tubes that would reduce residue buildup when firing high propellant charges (U.S. Army, 2016). Other improvements, like continued upgrades to the Digital Fire Control System, could aid the

M777 in remaining accurate and lethal throughout an extended lifespan. Factors like mobility and survivability, would remain unchanged with this alternative, and it would only delay the inevitable end of service life, still necessitating the identification of an eventual replacement.

Continued use of the M777 could also include transitioning to the M777-ER. Currently undergoing design and testing, the M777-ER is an extended-range variant of the M777A2, built to range targets in excess of 70 km (Wasserbly, 2017). This extra range is made possible by increasing the tube's length from 39-calibers to 55-calibers, adding nearly six feet of length to the cannon (Wasserbly, 2017). While it weighs approximately 1,000 lbs. more than the M777A2, it remains light enough for external transport by organic Marine Corps aircraft (Wasserbly, 2017). This alternative would not only continue to use the proven M777 platform, but would also close capability gap with regard to range.

2. Non-developmental Item

Another alternative is to purchase a non-developmental item (NDI) wheeled howitzer. Similar in concept to a commercial-off-the-shelf (COTS) system, an NDI is a previously developed system that is exclusively for government use, including that of foreign governments (Defense Acquisition University, n.d.). This alternative includes the purchase of existing foreign wheeled howitzers, requiring little or no modification. This concept is supported by the Marine Corps Operating Concept's encouragement to leverage COTS systems in order to aid in cheaper and expedited fielding of equipment (United States Marine Corps, 2016).

If an NDI is deemed the best alternative, there are numerous existing systems, already in use, for consideration (Trevithick, 2018a). Systems like Sweden's ARCHER, France's CAESAR, or Israel's ATMOS 2000 are wheeled systems employed by allies that would likely require minimal modifications (Foss, 2009b). Other manufacturers such as KMW, maker of the German tracked PzH2000, have demonstrated the willingness to convert their systems into wheeled variants (Foss, 2014). Regardless of which system, electing a currently available and proven system could present a fast and reliable means of acquiring a wheeled self-propelled howitzer.

3. Hybrid

Modifying and mounting the M777 to vehicles already in the Marine Corps inventory presents another wheeled howitzer alternative. There is discussion among the artillery community to build a prototype of this concept, which would be similar to the French CAESAR. This conceptual prototype, referred to as BRUTUS would attach the cannon assembly of the M777 to a 7-Ton MTVR, a commonly used truck already in the Marine Corps inventory (C. Hatch, W. Weisnet, & E. Wergano, interview with author, 5 June 2018; Oshkosh Defense, 2014). BRUTUS, or another similar hybrid system, would likely draw upon soft recoil technology (Hatch et al., 2018), similar to that developed by Mandus Group and demonstrated by the Hawkeye (AM General, n.d.-a). This soft recoil concept moves the cannon assembly forward just prior to firing, providing an offsetting motion to the recoil of firing (Trevithick, 2018a; Wynes & Bowrey, 2013). Soft recoil technology generates considerably less recoil when firing, thus reducing weight and the need for spades or stabilizers to anchor the cannon (Trevithick, 2018a). A lighter weight system, combined with not having to dig out a spade, can aid in reducing emplacement and displacement times, thereby improving the system's mobility and survivability.

4. New Howitzer Program

A final alternative is to initiate a new howitzer program, incorporating any specific requirements needed by the Marine Corps to combat emerging threats. Initiating a new program would likely be the most expensive and time-consuming alternative. This alternative would likely incorporate the newest technologies, but would also require the associated costs of research, development, and testing.

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III. METHODOLOGY

To conduct this study, the analysis uses a capabilities-based assessment (CBA) framework, and multi-criteria decision making (MCDM) methodology. As one of the first steps in the acquisition process, the CBA is intended to focus on identifying the operational problem that is faced, defining the capability gaps that exist, and developing possible methods for resolution (Office of Aerospace Studies, Air Force Material Command, 2014). The ultimate objective is to identify potential solutions for the identified capability gaps. This study's analysis mirrors steps six and seven the CBA nine-step framework (see Figure 7), with steps one through five covered in Chapter II. While a standard CBA includes a cost analysis in step eight, this study focuses exclusively on the solution analysis, also known as the effectiveness analysis (Office of Aerospace Studies, Air Force Material Command, 2014).

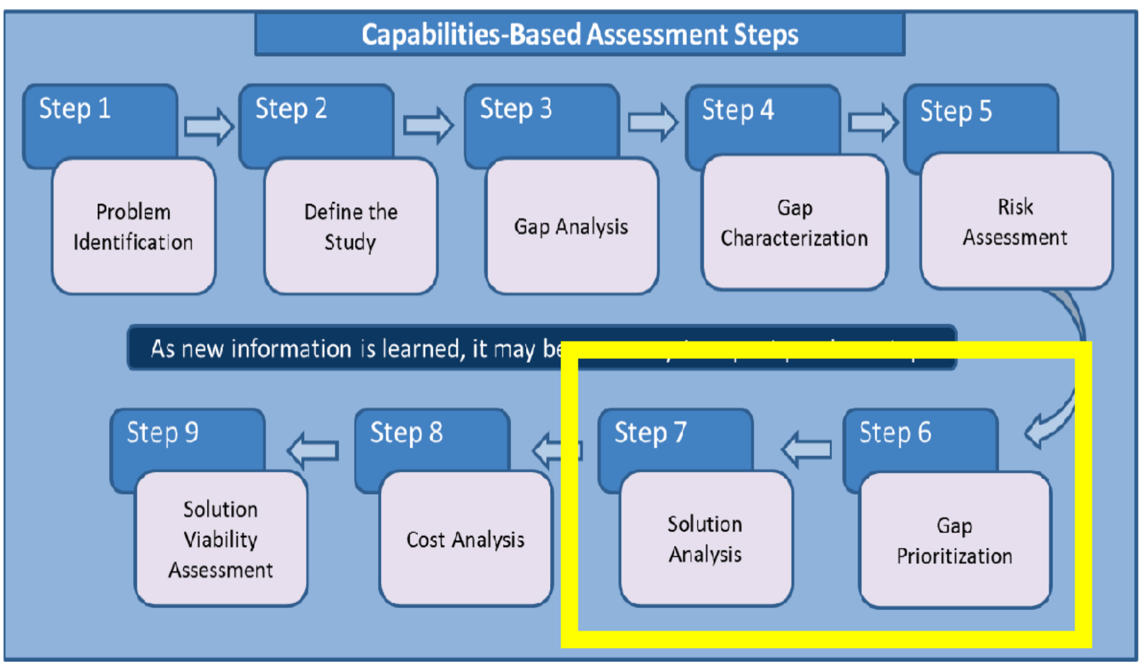

Figure 7. Capabilities-Based Assessment Steps in Analysis. Adapted from Office of Aerospace Studies, Air Force Material Command (2014).

While CBAs traditionally incorporate both material and non-material solutions, the emphasis of the analysis will be on the material alternatives. Given this focus on material solutions, the analysis will also draw upon methodologies for an analysis of alternatives (AOA). An AOA is a method of analytically comparing potential alternatives to a problem, and it is conducted early in the acquisition life cycle so that selection decisions may be made objectively (Georgiadis, Mazzuchi, & Sarkani, 2013; Department of Defense, 2004). As is done in a traditional AOA, this analysis describes the alternatives for consideration, establishes how performance and effectiveness are measured, and conducts a comparative analysis of each system's effectiveness (Department of Defense, 2004).

In order create a more robust and balanced evaluation, this analysis employs multi-criteria decision making (MCDM). MCDM is a means of combining qualitative assessments with quantitative measurements in order to better assess each system's overall effectiveness (Georgiadis et al., 2013). MCDM is commonly used in systems engineering, and other design-related fields, where it enables numerous, often disparate, capabilities to all be incorporated into a single overall measurement (Georgiadis et al., 2013). This broader assessment of a system's capabilities results in a more thorough assessment of performance, and ensures that all factors are considered when comparing the various alternatives.

Multi-Criteria Decision Making (MCDM), as described by Georgidis, Mazzuchi, and Sarkani, is conducted in three steps (Georgiadis et al., 2013):

1. "Determining the relevant criteria and alternatives"
2. "Attaching numerical measures to the relative importance (weights) of the criteria and to the impacts of the alternatives on these criteria"
3. "Processing the numerical values to determine the ranking of each alternative"

In order to effectively conduct MCDM, each step requires a number of other processes. The method for each step of the MCDM process is explained in the remainder of this chapter using an example set of data.

A. DETERMINING ALTERNATIVES

In order to conduct an effective AOA and yield the most insight possible, multiple specific alternatives must be considered. Worldwide there are dozens of potential artillery platforms for consideration in the AOA. The number of alternatives included must, however, be limited to a manageable number in order for the analysis to be effective (Department of Defense, 2004). Given this study's focus on wheeled cannon feasibility, the alternatives are limited to wheeled cannon alternatives. Among the wheeled systems in the world, the alternatives are limited to the most popular and prolific alternatives discussed among the artillery community, aligning with institutional guidance to assess preexisting feasible alternatives (Morrow, 2011; United States Marine Corps, 2016).

The analysis introduces each of the selected alternatives, along with the capability specifications for incorporation. Information on each system is from a combination of open source databases, and manufacturer literature available to the public. The analysis explains any assumptions made, as well as the rationale for each system's inclusion in the analysis.

B. DETERMINING REQUIREMENTS

As listed in the first step of MCDM, relevant criteria for evaluation must also be identified (Georgiadis et al., 2013). These criteria are considered the system's top-level requirements and are the paramount concern for fulfilling the identified needs of the user. These requirements are then addressed by incorporating various design characteristics into the system (Department of Defense, 2015).

In the absence of officially identified requirements, this analysis utilizes characteristics of interest, as outlined by PM-TAS. In February 2018, PM-TAS released a document soliciting manufacturers and developers to propose wheeled cannon designs for future use in the Army and Marine Corps (Army Contracting Command, 2018). Within the document were ten "high level physical/performance characteristics" that were of interest to PM-TAS (Army Contracting Command, 2018). These ten characteristics serve as the basis for the requirements in the analysis.

C. PAIRWISE COMPARISON OF REQUIREMENTS

Among the various requirements of a system, some may be considered more essential than others. This concept, described as "military worth" in the *Defense Acquisition Guidebook*, represents a combination of the critical tasks that the system must be capable of conducting (Department of Defense, 2004). In the absence of specific requirements, or prioritized tasks, the relative importance of requirements can be determined through other means. In order to account for any requirement priorities, this analysis employs a method known as the analytical hierarchy process (AHP). This process mathematically determines the relative weights for otherwise intangible requirements, aiding in the overall assessment of the alternatives (Saaty, 2008).

Included in the use of the AHP method is the use of pairwise comparisons. Pairwise comparisons pair the various, often competing, requirements and through a series of one-to-one comparisons. These numerous comparisons produce an overall importance of each requirement within the greater system (Saaty, 2008). Comparisons are conducted for each possible combination of paired requirements. With every one-on-one comparison conducted, the overall importance of a requirement is then mathematically determined, resulting in a weighting scheme that reflects requirement importance (Saaty, 2008). This weighting allows for the most important design characteristics to be properly assessed, and prevents the unfair assumption that all requirements are equal. The determined weights can then be applied to normalized capabilities, thus providing an overall measure of effectiveness for each alternative (Georgiadis et al., 2013; Saaty, 2008).

1. Requirement Comparison Scale

To initiate the pairwise comparison, each requirement must be compared against one another. This analysis conducts the comparison on a scale of 1–5 using numbers on one side, and their inverse on the other (Maritan, 2015; Saaty, 2008). A score of (1) represents indifference between the two requirements, indicating that the two requirements are thought to be equally important (see Table 6).

Table 6. Example Pairwise Comparison

Top-Level System Requirements										
Requirement 1	5	4	3	2	1	0.50	0.33	0.25	0.20	Requirement 2
Requirement 1	5	4	3	2	1	0.50	0.33	0.25	0.20	Requirement 3
Requirement 1	5	4	3	2	1	0.50	0.33	0.25	0.20	Requirement 4
Requirement 1	5	4	3	2	1	0.50	0.33	0.25	0.20	Requirement 5
Requirement 2	5	4	3	2	1	0.50	0.33	0.25	0.20	Requirement 3
Requirement 2	5	4	3	2	1	0.50	0.33	0.25	0.20	Requirement 4
Requirement 2	5	4	3	2	1	0.50	0.33	0.25	0.20	Requirement 5
Requirement 3	5	4	3	2	1	0.50	0.33	0.25	0.20	Requirement 4
Requirement 3	5	4	3	2	1	0.50	0.33	0.25	0.20	Requirement 5
Requirement 4	5	4	3	2	1	0.50	0.33	0.25	0.20	Requirement 5

The template for this pairwise comparison was created by Dr. Clifford Whitcomb, a distinguished professor at the Naval Postgraduate School (K. Giles, email to author, August 22, 2018).

As depicted in Table 6, Requirement 1 is assessed to be more important than Requirement 2, receiving a score of (3). Similarly, Requirement 1 is considered more important than Requirement 3, and scores a (2). Requirement 1 is considered less important than Requirement 4, and receives a score of (0.25), or the inverse of a score of (4) due to its direction. Requirements 1 and 5 are considered equal and are given a (1). This process of scoring is repeated, until all requirements have been compared against each other.

2. Pairwise Comparison Matrix

Scores identified in Table 6 are input into a pairwise comparison matrix (see Table 7). The matrix format has a space for comparison of each requirement twice—i.e., Requirement 2 to 3 and Requirement 3 to 2. Cells in grey represent the duplicate scoring and are populated with the inverse of the input score. When each requirement is compared against itself it receives a score of 1, representing indifference.

Table 7. Example Pairwise Comparison Matrix

	Criteria	Requirement 1	Requirement 2	Requirement 3	Requirement 4	Requirement 5	
Criteria		1	2	3	4	5	**Weights**
Requirement 1	1	1.000	3.000	2.000	0.250	1.000	0.216
Requirement 2	2	0.333	1.000	3.000	1.000	0.333	0.157
Requirement 3	3	0.500	0.333	1.000	2.000	1.000	0.154
Requirement 4	4	4.000	1.000	0.500	1.000	0.250	0.193
Requirement 5	5	1.000	3.000	1.000	4.000	1.000	0.281
		0.146	0.120	0.133	0.121	0.279	1.000
							Check

The template for this pairwise comparison matrix was created by Dr. Clifford Whitcomb, a distinguished professor at the Naval Postgraduate School (K. Giles, email to author, August 22, 2018).

The output of the matrix are weights listed in the righthand column. These weights indicate the degree of the overall importance of each requirement when compared to every other requirement. With these weights, the analysis appropriately reflects the relative importance of each requirement.

3. Prioritizing Requirements

The output of the pairwise comparison method is a set of prioritized requirements. These priorities are therefore largely dependent on the scores assigned through the various one-to-one comparisons. This subjectivity is a common source of criticism of this method of analysis (Georgiadis et al., 2013). While there are numerous possible methods for determining relative importance, they are all similarly subjective in nature. One common alternative is to survey various subject matter experts in the field, and use the survey results to assign the scores of relative importance (Georgiadis et al., 2013). Surveys can also yield subjective results, as they are contingent on the pool of interviewed subjects. For example, if the pool of surveyed individuals all subscribe to a certain tactical school of thought, the analysis will reflect those biases accordingly, thereby losing the desired objectivity.

For this analysis, the scores assigned to each requirements' importance are based upon the findings from the literature review, previous studies, and guiding Marine Corps doctrine. Each comparison is accompanied by a justification and references indicating the rationale for each score's assessment.

D. RELATING REQUIREMENTS TO CHARACTERISTICS

In order to fulfill a system's various requirements, system characteristics are incorporated into the design. Another assessment is made in order to determine the degree to which a characteristic addresses a requirement. Each design characteristic in a system does not always relate directly to a single requirement. Instead, a requirement may relate to a combination of characteristics, or it may relate to multiple design characteristics to varying degrees. In order to account for this inconsistent relationship, the weighted requirements from the pairwise comparison are related to the functions that fulfill those requirements.

To measure the degree of each relationship, this analysis uses a quality function deployment (QFD) matrix. The QFD is a concept originally developed by Toyota in order to address quality control and to meet customer demands (Maritan, 2015). The concept of QFD is complimentary to the AHP process, and aids in identifying the strength of correlations between system requirements and the design characteristics (Maritan, 2015).

The scale in this analysis is 1–3–5, denoting a low, medium, and high relationship, respectively, between characteristics and requirement (see Table 8). No score denotes no significant relationship between the design characteristic and the requirement. The matrix takes the numerical relationships between the two, and multiplies them by the weighted importance of each requirement. As in the pairwise comparison, the assessment of the relationship between the requirement and the characteristic is based upon the literature review.

Table 8. Example QFD

		Design Characteristics					
Customer Requirements	Weights	Characteristic 1	Characteristic 2	Characteristic 3	Characteristic 4	Characteristic 5	
Requirement 1	0.216	5					
Requirement 2	0.157		5				
Requirement 3	0.154		3	5			
Requirement 4	0.193			3	1	3	
Requirement 5	0.281					1	
Check Sum	1.00						
Weighted Performance		1.082	1.244	1.346	0.193	0.859	4.7
Performance Percentage		0.229	0.263	0.285	0.041	0.182	1.000
							Check

The template for this QFD matrix was created by Dr. Clifford Whitcomb, a distinguished professor at the Naval Postgraduate School (K. Giles, email to author, August 22, 2018).

Multiplying the weight by the relationship strength, and summing the total, results in a weighted performance score for that characteristic. Dividing the characteristic's weighted performance by the cumulative weighted performance results in a performance percentage. This performance percentage serves as the final weight that is applied in the comparative analysis. This weight incorporates the relative importance of the requirement, as well as the degree to which it fulfills the requirement.

E. NORMALIZATION

While MCDM enables various measurable capabilities to be incorporated into an overall measure of effectiveness, they must first be normalized into like units. Normalization allows for each characteristic, regardless of measurement or scale, to be compared in a common medium. The method of normalization applied to this analysis is known as Min-Max Transformation. Among the various values within each design characteristic, the minimum and maximum values are applied using the following equation (Shanmugam & Chattamvelli, 2015).

$$\frac{X - Xmin}{Xmax - Xmin}$$

This Min-Max Transformation allows each value to be compared against the overall range of values for that particular characteristic (Shanmugam & Chattamvelli, 2015). This normalization is applied to each characteristic, resulting in all scores falling between 0–1. In order to make the values easier to comprehend, they are multiplied by (10), resulting in values on a standard 0–10 scale. This revised equation is the following

$$10\left(\frac{X - Xmin}{Xmax - Xmin}\right).$$

This method of normalization is dependent on the identification of minimum and maximum values within each category. For this analysis, the maximum values are assigned using the highest values discovered through the research, which includes values from both existing system capabilities and values from emerging technology. The minimum values used are those considered unacceptable for use in the Marine Corps and are well below any current system capabilities.

F. ANALYSIS OF ALTERNATIVES

With the requirements, design characteristics, and alternatives identified, and all values normalized, the data is ready for the comparative analysis. Continuing the AHP methodology, the identified weights are applied to the system specifications of the alternatives (Georgiadis et al., 2013). This method is commonly used, and results in a single unitless score that represents the overall weighted performance of each system (Georgiadis et al., 2013; Maritan, 2015; Saaty, 2008).

The inputs for this step are the normalized capability specifications of each alternative, and the weighting of each design characteristic, as identified in the QFD step. The specifications are multiplied by the weights, and the value of each alternative's capabilities are summed (see Table 9). The result is an overall score from 0–10, representing that system's overall performance. Higher overall scores indicate that the system's capabilities align with the desired goal of the system. These scores, and subsequent ranking of alternatives, are the ultimate objective of the analysis.

Table 9. Example Alternative Comparison

	Characteristic 1	Characteristic 2	Characteristic 3	Characteristic 4	Characteristic 5	
Weight	**0.216**	**0.157**	**0.154**	**0.193**	**0.281**	1.000
Goal	10	10	10	10	10	10.000
Threshold	4	8	3	7	8	6.144
Minimum	0	0	0	0	0	0.000
Alternative 1	3	9	5	4	7	5.587
Alternative 2	2	8	8	2	5	4.639
Alternative 3	1	5	3	7	7	4.443

G. SENSITIVITY ANALYSIS

The procedures employed in the analysis are admittedly subjective in some regards. The use of MCDM for the assessment of top-level requirements relies largely on the informed evaluation of the researcher, and the direction or magnitude of the comparative ranking may be contested (Georgiadis et al., 2013). In order to account for this subjectivity, a sensitivity analysis is conducted with multiple iterations of the analysis (Georgiadis et al., 2013). Each iteration alters the scoring in the pairwise comparison of top-level requirements. These adjustments in turn effect the weighting scheme, placing emphasis on design characteristics that are different from the original assessments made by the researcher. Rankings from each analysis are then determined and trends in system performance can be assessed.

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IV. ANALYSIS

This analysis assesses numerous alternatives in order to address the growing capability gap faced by Marine Corps artillery. This study conducts an analysis of alternatives, while also incorporating multi-criteria decision making, pairwise comparison, and data normalization to provide an informed assessment.

A. ALTERNATIVE IDENTIFICATION

To conduct the analysis of alternatives, the field of potential alternatives is first narrowed down from the dozens of worldwide artillery systems. As discussed in Chapter III, PM-TAS provided insight into four broad courses of action being considered for the potential incorporation of a wheeled cannon in the Marine Corps (C. Hatch, W. Weisnet, E. Wergano, interview with author, 5 June, 2018). Of the four courses of action, three align with the most popular and discussed systems (see Table 10). The option to initiate a new wheeled howitzer program has no means of assessment and will not be considered further.

Table 10. Alternatives for Consideration

Course of Action	Alternative
SLEP of the M777 program	M777
	M777-ER
Purchase a Non-Developmental Item (NDI) wheeled howitzer	Hawkeye
	ARCHER
	CAESAR
Develop a hybrid wheeled howitzer using the M777 and an existing truck	BRUTUS
	BRUTUS-ER
Initiating a new wheeled howitzer program	Not explicitly included

The identified alternatives are not only among the most popular wheeled artillery systems, but each offer their own set of unique traits and capabilities for consideration. Based on the identified courses of action and associated alternatives, the analysis compares the current Marine Corps platform, the M777, against a selection of the most popular foreign systems and domestic concepts. Emerging concepts include the extended range variant of the M777, and both a standard and extended range wheeled howitzer concept, known as BRUTUS. Descriptions and unique aspects of each alternative are provided below. A detailed table with specific system capabilities for howitzers worldwide can be found in Appendix B.

1. M777

One alternative is to continue using the M777 towed howitzer. The M777 is regarded as one of the best towed cannons in the world (Gordon et al., 2015), and its towed concept makes the M777 the lightest-weight cannon among the alternatives. This light weight is an attractive feature given the expeditionary requirements of the Marine Corps. The towed concept does have its shortcomings, as discussed in Chapter II. Chief among the shortcomings is the system's inability to move independent of its prime mover, and its slow emplacement and displacement times (Appendix B; Clark, 2003; Gannon, 2013; Lankford, 2000). Additionally, the M777 is currently scheduled to reach the end of its service life in 2023 (United States Marine Corps, 2018).

This alternative assumes the currently published capabilities of the M777A2. There are ongoing efforts, such as the application of chrome tubes, that are intended to improve and modify the M777, improving its performance and extending its service life (United States Marine Corps, 2018; U.S. Army 2016). These efforts are assumed to continue with the selection of this alternative, enabling the service life to extend beyond its current end date.

2. M777-ER

The M777-ER is the newest variant of the M777 family, and has a longer range compared to the M777A2. Ongoing testing of the system has proven the ability to fire in excess of 70 km (Wasserbly, 2017). This is achieved by extending the length of the cannon tube approximately six feet, changing it from 39 calibers to 55 calibers (Wasserbly, 2017). The system's specifications are assumed to otherwise be that of the currently fielded M777A2.

3. Hawkeye

The Hawkeye is a wheeled howitzer prototype developed by Mandus Group. The system employs a 105 mm cannon on top of a HMMWV, and incorporates soft recoil technology (AM General, n.d.-a; Mandus Group, 2016). This system has a significantly shorter range than the other alternatives, but boasts a combination of light weight and independent mobility. The cannon and recoil system can theoretically be applied to platforms other than the HMMWV; however, this analysis assumes the use of the HMMWV. Publicly published information on this system is incomplete, so some data is derived using specifications of its components, the M1152 HMMWV and the M119 cannon (AM General, n.d.-a). While a displacement time was published, an emplacement time was not (Cox, 2017). The emplacement time for this analysis conservatively assumes that it is double that of the displacement time.

4. ARCHER

The Swedish-made ARCHER is a 155 mm/52-caliber howitzer affixed to a wheeled Volvo truck platform (BAE Systems International, n.d.). ARCHER incorporates the most technologically advanced capabilities among the alternatives. The cannon is capable of high rates of fire, 8-round multiple round simultaneous impact (MRSI) missions, and rapid emplacement and displacement (BAE Systems International, n.d.; Jane's by IHS Markit, 2018e). Most of these capabilities are enabled through automated systems, such as its auto-loader (BAE Systems International, n.d.; Jane's by IHS Markit, 2018e). This system is capable of being operated by a single person, and can be fired without the crew departing the armored cab (BAE Systems International, n.d.). The tradeoff of such advanced firepower is the size and weight of the howitzer, which impacts the mobility and transportability of the system.

5. CAESAR

CAESAR is among the most popular wheeled howitzers currently fielded worldwide (Gordon et al., 2015; Jane's by IHS Markit, 2018p). Developed by the French, it is also used by countries such as Thailand and Saudi Arabia, and it has proven effective in combat in Afghanistan, Lebanon, and Mali (Gordon et al., 2015; Jane's by IHS Markit, 2018p). Similar to ARCHER, CAESAR employs the NATO 155 mm standard round and uses a 52-caliber gun, giving it longer range than the M777 (Appendix B; Gordon et al., 2015). The cannon is built primarily on either a Mercedes or Renault truck chassis, and provides an alternative that is lighter than the ARCHER, and has better firepower and independent mobility than the M777 (Jane's by IHS Markit, 2018p).

6. BRUTUS

BRUTUS is a conceptual system that aims to leverage systems already in the Marine Corps inventory, combining the M777 with its prime mover (C. Hatch, W. Weisnet, E. Wergano, interview with author, 5 June, 2018). This concept would result in a system similar to the foreign CAESAR or ARCHER systems, but would use components already used in the Marine Corps, alleviating some maintenance, supply, and training concerns. Inspired by Mandus Group's 105 mm Hawkeye, this larger 155 mm variant could theoretically also employ a soft recoil mechanism to reduce weight (C. Hatch, W. Weisnet, E. Wergano, interview with author, 5 June, 2018).

This system is currently only a concept, and therefore has no actual specifications to analyze. The analysis assumes that this system has the same firing specifications of the current M777, and the same mobility as the Oshkosh MTVR. The dimensional data is derived by combining the two platforms' measurements. The displacement time is assumed to be similar to that of the Hawkeye, and its emplacement time is assumed to be double the displacement time.

7. BRUTUS-ER

While BRUTUS employs the M777, this alternative instead incorporates the M777-ER. This alternative's firepower data is that of the M777-ER, while mobility data is from the MTVR. Similar to BRUTUS, the dimensional data is a combination of the two platforms' measurements, and emplacement and displacement times are based upon that of the Hawkeye.

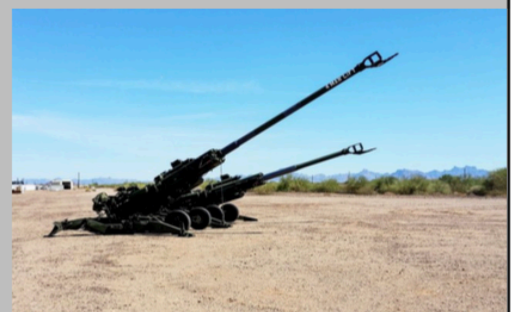
B. ALTERNATIVE DATA

Data for all considered systems is from openly published sources, and is consolidated in Appendix B. Only the selected alternatives, and their relevant capabilities, are used in the analysis (see Figure 8).

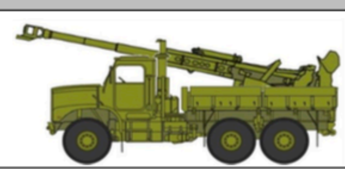
Hawkeye Wheeled SP 105mm Howtizer			
Max Range:	19 km	Independent Mobility:	Yes
Max Rate of Fire:	8 Rds/Min	# Cannons per CH-53E/K:	1
MRSI Capable:	1 Rd/Msn	# Cannons per LCU:	8
Time to Emplace:	60 sec	# Cannons perLCAC:	8
Time to Displace:	30 sec	Survivability:	Medium
Driving Speed:	70 mph		

CAESAR Wheeled SP Howtizer			
Max Range:	58 km	Independent Mobility:	Yes
Max Rate of Fire:	6 Rds/Min	# Cannons per CH-53E/K:	0
MRSI Capable:	1 Rd/Msn	# Cannons per LCU:	4
Time to Emplace:	35 sec	# Cannons perLCAC:	4
Time to Displace:	30 sec	Survivability:	Medium
Driving Speed:	62.1 mph		

ARCHER Wheeled SP Howtizer			
Max Range:	50 km	Independent Mobility:	Yes
Max Rate of Fire:	9 Rds/Min	# Cannons per CH-53E/K:	0
MRSI Capable:	6 Rd/Msn	# Cannons per LCU:	2
Time to Emplace:	20 sec	# Cannons perLCAC:	1
Time to Displace:	20 sec	Survivability:	High
Driving Speed:	43.5 mph		



M777-ER Lightweight Towed Howitzer w/ MTVR			
Max Range:	70 km	Independent Mobility:	Yes
Max Rate of Fire:	4 Rds/Min	# Cannons per CH-53E/K:	1
MRSI Capable:	1 Rd/Msn	# Cannons per LCU:	2
Time to Emplace:	180 sec	# Cannons perLCAC:	2
Time to Displace:	120 sec	Survivability:	Low
Driving Speed:	60 mph		



BRUTUS Wheeled SP Howitzer			
Max Range:	40 km	Independent Mobility:	Yes
Max Rate of Fire:	4 Rds/Min	# Cannons per CH-53E/K:	0
MRSI Capable:	1 Rd/Msn	# Cannons per LCU:	4
Time to Emplace:	60 sec	# Cannons perLCAC:	4
Time to Displace:	30 sec	Survivability:	Medium
Driving Speed:	60 mph		

M777 Lightweight Towed Howitzer w/ MTVR			
Max Range:	40 km	Independent Mobility:	Yes
Max Rate of Fire:	4 Rds/Min	# Cannons per CH-53E/K:	1
MRSI Capable:	1 Rd/Msn	# Cannons per LCU:	2
Time to Emplace:	180 sec	# Cannons perLCAC:	2
Time to Displace:	120 sec	Survivability:	Low
Driving Speed:	60 mph		

No Picture

BRUTUS-ER Wheeled SP Howitzer			
Max Range:	70 km	Independent Mobility:	Yes
Max Rate of Fire:	4 Rds/Min	# Cannons per CH-53E/K:	0
MRSI Capable:	1 Rd/Msn	# Cannons per LCU:	4
Time to Emplace:	60 sec	# Cannons perLCAC:	4
Time to Displace:	30 sec	Survivability:	Medium
Driving Speed:	60 mph		

Data. Adapted from: Appendix B. Hawkeye Picture. Source: Mandus Group (n.d.). CAESAR Picture. Source: Jane's by HIS Markit, (2018p). ARCHER Picture. Source: Jane’s by IHS Markit (2018e). M777-ER Picture. Source: Real Clear Defense (2018). BRUTUS picture. Adapted from: Department of the Army (n.d.-b). M777 Picture. Source: Graf (2014).

Figure 8. Howitzer Specifications

C. REQUIREMENT IDENTIFICATION

This analysis considers the features alluded to in the 2018 sources sought document published by PM-TAS as the basis for the system requirements (Army Contracting Command, 2018). These ten features (see Table 11) are consistent with attributes considered relevant throughout the literature review as well.

Table 11. Ten System Requirements

Mobility	First Round Response
Transportability	Fire Control
Range	Cannon Caliber (bore and length)
Rate of Fire	Weight
Emplacement/Displacement	Crew Size

While the sources sought discusses ten aspects for consideration, this analysis only employs five of them. First round response and fire control are not easily measured using open source data, and are difficult to compare. Cannon caliber, while certainly important, impacts the system's range and the size of the system, both of which are already addressed through other requirements. Weight is a component of transportability, and is addressed through that requirement. Finally, crew size is ultimately a product of which alternative is chosen, not vice versa. Given these omissions, only the five requirements are used in the remainder of the analysis (see Table 12).

Table 12. Five System Requirements

Mobility
Transportability
Range
Rate of Fire
Emplacement/Displacement

D. REQUIREMENT PRIORITIZATION

The five requirements are not necessarily of equal value, and therefore are assigned appropriate weights that reflect each requirement's importance. Using a pairwise comparison, each of the requirements is compared against one another and rated on a scale of 1–5 on relative importance (see Table 13). The assessed importance of each comparison is accompanied with a section justifying the selection of that score.

Table 13. Pairwise Comparison

Top-Level System Requirements										
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Transportability
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Range
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Range
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Range	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Range	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Rate of Fire	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement

1. Mobility vs. Transportability

The importance of transportability to the Marine Corps mission is clearly stated in Marine Corps Operating Concept 2016. There it states that the Marine Corps should "develop future forces and equipment that can readily deploy aboard amphibious warfare ships, Military Sealift Command vessels, strategic airlift, and organic MAGTF aviation assets" (United States Marine Corps, 2016, p. 22). This is one of multiple references throughout the document that speaks to the institutional emphasis on transportability. Much of the concern with mobility is addressed through the analysis's focus on wheeled alternatives. Road speed and cross-country speed have not been identified as particular shortcomings of current systems (Field, 2004; Gordon et al., 2015). While it is important that the system be mobile on and off road, all of the considered alternatives have similar mobility capabilities, but have notable differences in transportability. With transportability as the greater institutional challenge, it is given a stronger relative score compared to mobility.

2. Mobility vs. Range

Range, too, is considered more essential than mobility. The Marine Corps Operating Concept specifically notes the need to "develop fire support systems providing the range, precision and agility to survive against peer fires system" (United States Marine Corps, 2016, p. 22). As firepower is one of the more notable capability shortcomings of current systems (see Appendix B), addressing it is crucial. While mobility is certainly beneficial, its relative value to the system is only truly realized once the howitzer is within range of the enemy. If a howitzer is able to operate outside of the enemy's artillery range, the need for rapid mobility is considerably diminished. For this reason, range maintains a stronger relative value over that of mobility.

3. Mobility vs. Rate of Fire

Howitzers that are capable of high rates of fire often do so by using large, heavy, automated systems. High rates of fire also use ammunition at a faster rate and thus require large magazines and robust supply lines to support operations. Having a high rate of fire, given the current technologies, is adverse to the system's mobility due to this increased weight and size. While howitzers like ARCHER and the PzH2000 boast high rates of fire, they also have slower speeds and limited maneuverability when compared to their lighter counterparts (Appendix B; Kemp, 2007). While the Marine Corps Operating Concept calls for both a mobile force, and the ability to mass fires, mobility best aligns with the expeditionary nature of the Marine Corps mission (United States Marine Corps, 2016). Given the discussion of massed fires in the Marine Corps Operating Concept, and the importance of overcoming the firepower capability gap, the score should only mildly favor mobility.

4. Mobility vs. Emplacement/Displacement

Of the various tradeoffs, mobility and emplacement/displacement are the most aligned. Both mobility and emplacement facilitate the rapid support of maneuver units. Similarly, mobility and displacement are crucial to survival in a counterbattery environment (Foss, 2003, 2014; Hawkes, 2016). These are complimentary requirements and are both largely addressed through the consideration of wheeled howitzers (Foss, 2003, 2014; Hawkes, 2016). Due to the similar objective of both requirements, the importance of one over the other is negligible, and the two are considered of equal importance.

5. Transportability vs. Range

Based upon the guidance of the Marine Corps Operating Concept, both transportability and range are vital to success in future engagements but pose a notable tradeoff (United States Marine Corps, 2016). Range represents a large component of the greatest capability gap, which is firepower (Gordon et al., 2015). Achieving long range often requires larger cannons, increased weight, and reduced transportability. Exemplifying this tradeoff is the now retired EFSS. The EFSS lacked in range but excelled in transportability, ultimately failing to serve the needs of the Marine Corps (Jane’s by IHS Markit, 2017d; Trevithick, 2018b). Range is central to the concept of artillery and indirect fire support, and must be considered more important. The importance of transportability cannot be completely undervalued, as that still presents an instrumental component to Marine Corps operations. While range can be assessed as the more important requirement, the importance of transportability justifies only a slight favor toward range.

6. Transportability vs. Rate of Fire

While transportability is deemed less important than range, it remains more important than rate of fire. Worldwide, howitzers are capable of achieving high rates of fire, but often do so at the expense of weight and transportability (Appendix B; Kemp, 2007). Heavy auto-loading mechanisms and magazines make these platforms incompatible with many of the Marine Corps' ship-to-shore connectors. Along with high rates of fire come increased supply requirements and more transportability concerns. While the ability to fire rapidly is desirable, it comes with a predictable and exploitable weakness in transportability. Rate of fire can be compensated for by increasing the quality of howitzers fielded, or by alternative forms of fire support (Gordon et al., 2015). Transportability, however, has little substitution. For this reason, transportability is considered a more important requirement than rate of fire in this analysis.

7. Transportability vs. Emplacement/Displacement

When compared to transportability, emplacement and displacement's importance can be moderately diminished. Currently fielded systems, such as ARCHER, feature rapid emplacement and displacement times, but do so with heavy automated systems, thereby limiting transportability (BAE Systems International, n.d.; Kemp, 2007). A system that boasts impressive emplacement and displacement times remains useless if it is unable to reach shore in the first place. The challenge is to leverage similar technologies in a transportable manner, thus aligning with the Marine Corps' mission. While transportability is considered more critical, the importance of emplacement and displacement cannot be completely ignored as it facilitates the expeditious engagement of targets, and the reduced the risk of receiving counterfire (Foss, 2003; Hawkes, 2016). To ensure that emplacement and displacement are considered appropriately, the score in favor of transportability is kept to a minimum.

8. Range vs. Rate of Fire

While range and rate of fire combine to account for the greatest capability gap, range is considered more critical due to its implications in the battle the future (Burgess, 1997). In an A2AD environment, longer-range fires will be one of the greatest focal points

(Bonds et al., 2017). The Marine Corps Operating Concept specifically discusses this need for increased range for its fire support systems (United States Marine Corps, 2016). When faced with a counterbattery environment, superior range allows for the ability to fire beyond the enemy's range, negating their ability to return fire. Regardless of the rate of fire, if the system has a lesser range, and remains within the enemy's range, it remains vulnerable to counterfire. While not ideal, it is possible to compensate a low rate of fire with accuracy or with more systems (Gordon et al., 2015).

9. Range vs. Emplacement/Displacement

Addressing range is instrumental in overcoming the firepower capability gap. Guidance in the 2016 Marine Corps Operating Concept describes the need to "develop fire support systems providing the range, precision, and agility to survive against peer fires systems." (United States Marine Corps, 2016, p. 22). Rapid emplacement and displacement is beneficial as it facilitates engagement and survival while operating within the enemy's achievable range. Increased range, however, presents the potential to never be within the enemy's range (Burgess, 1997). Additionally, by possessing a long-range capability, any counterfire must also travel an equally farther distance, thereby increasing the time for displacement. Range, therefore, is considered a more important requirement, but only to a moderate degree, as emplacement and displacement still remain relevant in a counterfire-intensive environment.

10. Rate of Fire vs. Emplacement/Displacement

Rate of fire's ability to serve as a force multiplier is important, but is also contingent on the ability to displace rapidly. With counterbattery radar developments, the likelihood of detection upon firing is greater than ever, and the force of the future must be prepared for it (Gordon et al., 2015; United States Marine Corps, 2016). Assuming that every time a howitzer fires it is detected and subject to counterfire, it is imperative that the howitzer rapidly displace in order to survive and continue fighting (United States Marine Corps, 2016). A high rate of fire is beneficial in these circumstances, as it makes greater use of each exposure. When assessing the risk, however, it is more beneficial to fire a single round and safely displace to reengage, than to generate more rounds and risk destruction. Rate of fire remains a desirable characteristic as it optimizes the productivity of each exposure, therefore the favor toward emplacement/displacement is minimized.

E. PAIRWISE COMPARISON

The scores, previously assigned in Table 13, are placed into the pairwise comparison matrix (see Table 14). This chart depicts the same comparison of each requirement, placing the determined scores in the yellow boxes, and their inverse in the grey boxes. The result of the comparison is the weighted importance of each requirement, as assessed in the study.

Table 14. Pairwise Comparison Matrix

	Criteria	Mobility	Transportability	Range	Rate of Fire	Emplacement/Displacement	
Criteria		1	2	3	4	5	Weights
Mobility	1	1.000	0.333	0.333	2.000	1.000	0.132
Transportability	2	3.003	1.000	0.500	2.000	2.000	0.250
Range	3	3.000	2.000	1.000	3.000	3.000	0.383
Rate of Fire	4	0.500	0.500	0.333	1.000	0.500	0.095
Emplacement/Displacement	5	1.000	0.500	0.333	2.000	1.000	0.140
		0.118	0.231	0.400	0.100	0.133	1.000
							Check

Given each comparative assessment, the most important requirements, in order, are range, transportability, emplacement/displacement, mobility, and finally rate of fire. These weights are carried over into the QFD step to determine the final weighting scheme.

F. QUALITY FUNCTION DEPLOYMENT COMPARISON

With the requirements prioritized, they must be related to design characteristics that for incorporation into the system. Each design characteristic represents a measurable capability of the howitzer that allows for alternative comparison. Each of the elected design characteristics addresses at least one of the system requirements, which seeks to resolve one of the capability gaps of Marine Corps artillery (see Table 15).

Table 15. Requirements into Characteristics

Capability Gap	Requirement	Design Characteristic	Unit of Measure
Firepower	Range	Long Range	Kilometer
	Rate of Fire	High Rate of Fire	Rounds per minute
		MRSI Mission Capable	Number of Rounds
Mobility	Emplacement/ Displacement	Low Emplacement Time	Seconds
		Low Displacement Time	Seconds
	Mobility	Road Speed	Miles Per Hour
		Independently Mobile	Yes/No
Transportability	Transportability	Transportable by CH-53E/K	Cannons carried per trip
		Transportable by LCU	
		Transportable by LCAC	

In order to account for any overlap in requirement fulfillment, the QFD comparison aids in associating the requirements to the characteristics. Employing a 1–3–5 scale for low, medium, and high scoring, the QFD Comparison shows the degree to which each characteristic serves each requirement (see Table 16). The degree of each relationship enables characteristics that contribute to more than one requirement to be assessed accordingly.

Table 16. QFD Comparison Matrix

		Design Characteristics										
		Max Range	Max Rate of Fire	Max MRSI mission	Time to Emplace	Time to Displace	Driving Speed	Independently Mobile	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC	
Customer Requirement	Weights	km	Rds/min	Rds/Impact	Seconds	Seconds	MPH	Binary (Yes=1, No=0)	# Cannons	# Cannons	# Cannons	
Mobility	0.1322				3	3	5	5				
Transportability	0.2501								5	5	5	
Range	0.3829	5										
Rate of Fire	0.0948		5	3								
Emplacement/Displacement	0.1399				5	5		5				
Check Sum	1.00											
Weighted Performance		1.914	0.474	0.285	1.096	1.096	0.661	1.361	1.251	1.251	1.251	10.6
Performance Percentage		0.180	0.045	0.027	0.103	0.103	0.062	0.128	0.118	0.118	0.118	1.000

Mobility and Emplacement/Displacement account for the overlap in this particular analysis. The time it takes a system to emplace and displace has direct implications on the overall mobility of a system, not just on the act of emplacing and displacing. Likewise, independent mobility is strongly related to the ability to emplace and displace, as self-propelled howitzers of all types are proven superior in this regard.

The previously identified weights are multiplied by the strength of the relationship, and the values are summed. This process yields a weighted performance, and ultimately a performance percentage. This percent performance is the final weight to be applied in the analysis of alternatives. This weight now accounts for the relative importance of each requirement, as well as each characteristic’s degree of contribution to the requirements.

G. NORMALIZATION

In order to determine a single measure of effectiveness of each alternative, the various design characteristics, with their unique units of measure, are normalized. Normalized values are achieved by converting each characteristic's specifications into a score on a scale of 0–10. This unitless score is then multiplied by the previously determined weights, and the final measures of effectiveness are calculated.

The various specifications used are drawn from openly available resources, and are listed in full in Appendix B. Raw capability data, as depicted in Table 17, is compiled to facilitate the analysis (see Table 17). The values listed under "goal" represent a maximum potential capability achievable for each design characteristic. These maximum values are assigned based on a combination of the most advanced current capabilities in the world, and literature regarding future artillery technologies. The minimum values represent an estimate of the lowest acceptable scores for any future system. For comparative purposes, the row labeled "threshold" represents values that would be a reasonable advancement from current capabilities.

Table 17. Raw Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
Raw Values	Goal	100	10	6	30	30	75	1	1	15	10
	Threshold	70	6	4	75	60	60	1	1	2	2
	M777 w/MTVR	40	4	1	180	120	60	0	1	2	2
	M777-ER w/ MTVR	70	4	1	180	120	60	0	1	2	2
	Haweye	19	8	1	60	30	70	1	1	14	9
	ARCHER	50	9	6	20	20	43.5	1	0	3	1
	CAESAR	58	6	1	35	30	62.1	1	0	6	3
	BRUTUS	40	4	1	60	30	60	1	0	6	3
	BRUTUS-ER	70	4	1	60	30	60	1	0	6	2
	Minimum	10	1	1	240	240	40	0	0	1	1

With the specifications for each alternative identified, as well as the minimum and maximum values for each characteristic, the data is normalized (see Table 18). Using the equation discussed in Chapter III, and also depicted on the left side of Table 18, each specification receives a relative score between that characteristic's minimum and maximum values.

Table 18. Normalized Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
10(X-Xmin) (Xmax-Xmin)	Goal	10	10	10	10	10	10	10	10	10	10
	Threshold	7	6	6	8	9	6	10	10	1	1
	M777 w/MTVR	3	3	0	3	6	6	0	10	1	1
	M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1
	Haweye	1	8	0	9	10	9	10	10	9	9
	ARCHER	4	9	10	10	10	1	10	0	1	0
	CAESAR	5	6	0	10	10	6	10	0	4	2
	BRUTUS	3	3	0	9	10	6	10	0	4	2
	BRUTUS-ER	7	3	0	9	10	6	10	0	4	1
	Minimum	0	0	0	0	0	0	0	0	0	0

All scores are rounded to the nearest whole number.

Each alternative's specifications are now represented as a score on the scale of 0–10, with 10 representing a strong performance.

H. COMPARISON OF ALTERNATIVES

The comparison of the various alternatives is the ultimate objective of this analysis. Using the normalized specifications and prioritized requirements, comparing the selected alternatives yields the cannon best suited for the Marine Corps' future needs.

In the comparison of alternatives, alternative scores are multiplied against the respective design characteristic weights. The sum is taken of those weighted values, resulting in an overall score of a possible ten points. This final score represents a relative value that assesses the system's overall effectiveness in fulfilling the requirements (see Table 19).

Table 19. Weighted Comparison of Alternatives

	Max Range	Max Rate of Fire	Max MRSI mission	Time to Emplace	Time to Displace	Driving Speed	Independently Mobile	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC	
	km	Rds/min	Rds/Impact	Seconds	Seconds	MPH	Binary (Yes=1, No=0)	# Cannons	# Cannons	# Cannons	
Weight	**0.180**	**0.045**	**0.027**	**0.103**	**0.103**	**0.062**	**0.128**	**0.118**	**0.118**	**0.118**	1.000
Normalized Goal (Max)	10	10	10	10	10	10	10	10	10	10	10.000
Normalized Threshold	7	6	6	8	9	6	10	10	1	1	6.325
Normalized Minimum	0	0	0	0	0	0	0	0	0	0	0.000
M777 w/MTVR	3	3	0	3	6	6	0	10	1	1	3.377
M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1	3.976
Haweye	1	8	0	9	10	9	10	10	9	9	7.564
ARCHER	4	9	10	10	10	1	10	0	1	0	5.131
CAESAR	5	6	0	10	10	6	10	0	4	2	5.596
BRUTUS	3	3	0	9	10	6	10	0	4	2	4.977
BRUTUS-ER	7	3	0	9	10	6	10	0	4	1	5.446

The top-performing system, highlighted in yellow in Table 19, is the Hawkeye. With an overall effectiveness score of 7.5/10, the Hawkeye outperforms the other alternatives with this given weighting scheme. While not every value met or exceeded the threshold value, its overall effectiveness did.

I. SENSITIVITY ANALYSIS

While the analysis yielded one alternative as the most effective overall, that is only the outcome for that specific weighting scheme. When requirements are prioritized differently, the analysis yields different overall effectiveness scores. In order to account for this potential variation, multiple iterations of the analysis are conducted, each using different requirement scoring and prioritization. While any number of scoring combinations can be applied with this model, six additional trials are conducted. Below are the descriptions of all seven iterations the change in scoring.

1. The original analysis, which weighs requirement importance based upon the literature review and guiding doctrinal documents.

2. Range is considered the most important requirement, while all other requirements are set equal to one another. This assumption emphasizes the need to overcome the capability gap in firepower.

3. All requirements are set equal to one another. This scoring assumes that each requirement is equally important. This was a recommended method of prioritization from PM-TAS (C. Hatch, email to author, September 18, 2018).

4. The mobility requirement and displacement/emplacement requirement are increased, while all others are set equal. This requirement scoring is suggested by engineers at PM-TAS (C. Hatch, email to author, September 18, 2018).

5. All ten of the original requirements are considered in the analysis. Rather than narrowing the requirements down, all ten of the original points of interest, from the sources sought document, are incorporated. Scoring of the ten requirements is done in a similar manner to the original iteration, relying upon the literature review and doctrine for justification.

6. The original iteration's scoring is used, but redundancy in the QFD is reduced. The overlap between mobility and emplacement/displacement is removed, reducing the impact of those design characteristics. Redundancy in surface vessel compatibility is also reduced by only assessing the number of cannons that can fit on the LCAC, omitting the LCU.

7. The original iteration's scoring is used, but redundancy in the QFD is reduced. The overlap between mobility and emplacement/displacement is removed, reducing the impact of those design characteristics. Redundancy in surface vessel compatibility is also reduced by only assessing the number of cannons that can fit on the LCU, omitting the LCAC.

Through this combination of trials, the analysis attempts to reduce any subjectivity and bias that may be applied through the pairwise comparison or the QFD. Figures depicting each iteration's process are found in full in Appendix C.

The raw scores for all seven analyses are out of a possible ten points. The highest score for each iteration is highlighted in yellow (see Table 20).

Table 20. Raw Results of Sensitivity Analysis

	M777 w/ MTVR	M777-ER w/ MTVR	Hawkeye	ARCHER	CAESAR	BRUTUS	BRUTUS-ER
1. Original	3.38	3.98	7.56	5.13	5.60	4.98	5.45
2. Maximum Range	3.24	4.30	6.28	5.89	6.07	5.14	6.13
3. All Factors Equal	3.21	3.50	8.07	6.38	6.32	5.75	5.94
4. Increased Mobility/Emplacement/Displacement	3.17	3.31	8.75	7.62	7.87	7.39	7.48
5. Ten Factors	3.60	4.16	7.67	4.55	4.98	4.39	4.81
6. Less Redundancy and only LCAC	4.01	4.81	6.90	4.75	5.10	4.32	4.95
7. Less Redundancy and only LCU	3.94	4.75	6.96	4.98	5.31	4.54	5.34

By ranking the raw scores for each iteration, the top-performing systems are identified. The top-ranked system in each iteration is highlighted in yellow (see Table 21).

Table 21. Ranked Results of the Sensitivity Analysis

	M777 w/ MTVR	M777-ER w/ MTVR	Hawkeye	ARCHER	CAESAR	BRUTUS	BRUTUS-ER
1. Original	7	6	1	4	2	5	3
2. Maximum Range	7	6	1	4	3	5	2
3. All Factors Equal	7	6	1	2	3	5	4
4. Increased Mobility/Emplacement/Displacement	7	6	1	3	2	5	4
5. Ten Factors	7	6	1	4	2	5	3
6. Less Redundancy and only LCAC	7	4	1	5	2	6	3
7. Less Redundancy and only LCU	7	5	1	4	3	6	2

As demonstrated in Tables 20 and 21, the Hawkeye is unanimously the top performing alternative, regardless of requirement prioritization.

J. DOTMLPF-P IMPLICATIONS

While the results of the analysis suggest that any number of the alternatives are an improvement over the currently fielded M777, there are various other considerations whose implications must be considered. Replacing or supplementing the M777 with another system would require changes to supporting infrastructure, manpower, and tactics, among other aspects. It is therefore prudent to discuss some potential effects that a new system would have on doctrine, organization, training, materiel, leadership and education, personnel, facilities, and policy (DOTMLPF-P).

All of the discussed alternatives present beneficial changes to the force structure and manpower of artillery units, when compared to the M777. The wheeled systems in the analysis require fewer users to operate than the current M777, enabling for better use of manpower, a critical resource in the Marine Corps (see Figure 9). While a six-gun battery of M777's requires 42 cannoneers, six CAESARs require only 24, freeing 18 cannoneers to be used in other capacities (Appendix B). This available manpower could allow for the fielding of an additional three cannons. Similarly, Hawkeye is operated with a crew of four, meaning that the manpower of a current M777 battery could field 14 cannons.

Figure 9. Manning on the M777. Source: Military.com (n.d.).

The difference in weights and size of the various systems also presents an opportunity to field more howitzers per battery. Given the confined storage of amphibious ships, space is critical, and a smaller footprint pays dividends. By combining the cannon and prime mover into a single vehicle space, a battery can take up significantly less space. The BRUTUS concept would be just over half of the length of an M777 with its prime mover (Appendix B), creating enough linear space to potentially add more howitzers per battery (see Figure 10).

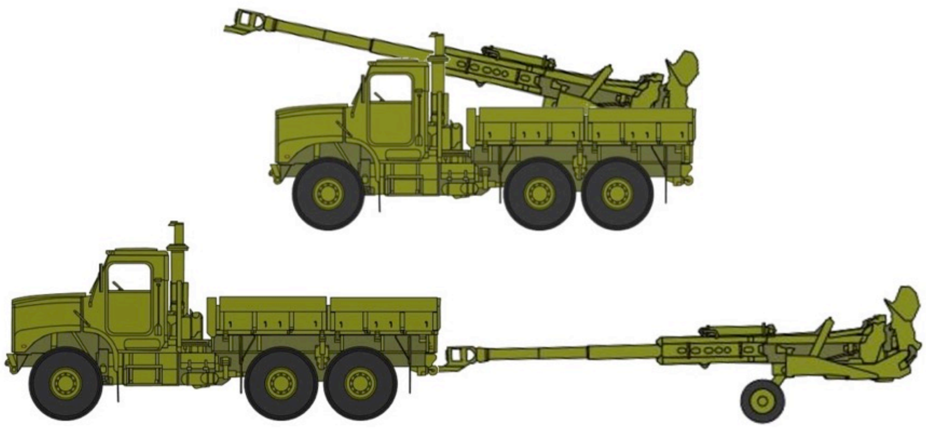


Figure 10. Comparison of Size. Adapted from Department of the Army (n.d.-b).

The difference in size has similar implications for ship-to-shore movement. Moving all six M777s and prime movers ashore requires either three LCACs or LCUs (Appendix B). Instead, a Hawkeye can fit up to nine systems on a single LCAC (see Figure 11) (Appendix B). The implications of echeloning an entire battery of cannons ashore on a single platform provides an invaluable asset to landing force commanders.

This picture depicts an LCAC carrying 12 HMMWVs. Weight constraints limit the Hawkeye to nine (Appendix B).

Figure 11. LCAC Carrying 12 HMMWVs. Source: Federation of American Scientists (2000).

The potential to increase the number of cannons per battery is the greatest organizational impact of a wheeled howitzer. Due to its more compact size and its reduced manpower requirements, units could theoretically increase the number of cannons employed, thereby increasing firepower and lethality of a single unit. With more effective systems and more efficient use of resources, a natural result may be to reorganize artillery units.

While any new system will certainly require training and education, Marine artillery is already in a position to reduce this impact. All Marine Corps artillerymen receive their training at Fort Sill, where the Army and Marine Corps currently combine to train artillerymen on the M777, M109, M119, M142, M270, and formerly on the EFSS (Department of the Army, n.d.-a). The artillery school structure clearly has the capacity to instruct various artillery platforms. Additionally, five of the seven discussed alternatives in the analysis employ a variation of these cannons currently included in instruction. Therefore, adaptations to training and education are considered minimal.

One of the more significant training implications resulting from the analysis is the need for improvement of the M777's emplacement and displacement times. In the analysis, the M777 emplacement and displacement times are considerably inferior to those of automated alternatives. While many of the wheeled systems' emplacement and displacement times are limited by physical system constraints, the M777's limiting constraint on emplacement and displacement time is partly dependent on the skill of the crew. The Marine Corps training and readiness manual calls for an artillery battery to conduct an emergency displacement within four minutes in daylight, and six minutes in darkness (United States Marine Corps, 2007). These times are higher than the displacement times used in the analysis and may reflect a more accurate performance. Similar disparities exist between the M777 emplacement times, and the emplacement training standard (United States Marine Corps, 2007). In the absence of an automated system, improving M777 emplacement and displacement times depends on the training of its crew.

Maintenance and supply for five of the seven alternatives would also prove negligible, as they employ systems currently fielded in the Army and Marine Corps. BRUTUS and Hawkeye deliberately incorporate cannons and vehicles already in the U.S. arsenal for this very reason, as repair parts and supporting infrastructure already exist. The technological complexity used in systems with soft recoil and automatic loading would, however, present new challenges, and would likely require the addition of new parts and maintainer training. All of the considered alternatives employ standard NATO caliber ammunition, allowing for the continued use of ammunition already in the U.S. arsenal (Appendix B).

Incorporating mobile and transportable wheeled howitzers would have rippling effects on Marine Corps doctrine, making it the most effected aspect. Among the areas for considered change are the implications to battery size and construct. Increasing the number of cannons per battery has a considerable effect on how fire support is best employed. More cannons can provide greater massed fires, or it can provide greater support of distributed operations and dispersed forces. Doctrine and tactics would, therefore, have to adapt to reflect these conceptual changes of employment.

In many regards the DOTMLPF-P considerations would require little change, should a wheeled howitzer be elected. The various alternatives considered in the analysis, were chosen in part for this minimal impact on the existing Marine Corps construct. In an environment where cost effectiveness and timeliness is paramount, the ease of incorporating one of the listed alternatives is a notable advantage.

K. FUTURE APPLICATIONS

Apart from the current capabilities of each of the discussed alternatives, there are a number of areas where advancing technologies can be incorporated. With rapidly changing technology providing improved capabilities, selecting an adaptable and flexible system is advantageous.

The Marine Corps Operating Concept calls for the need to develop greater shipboard fire support capabilities in order to combat future A2AD environments (United States Marine Corps, 2016). In October 2017, a Marine Corps HIMARS launcher successfully prosecuted targets on land, firing from the back of a U.S. Navy ship (see Figure 12)(United States Naval Institute, 2017). This potential for artillery to augment NSFS can serve as a force multiplier in a contested amphibious landing. With this capability, artillery could engage from the ship until its transition ashore, rather than depending on air and naval fire support alone.

Figure 12. HIMARS Firing from *USS Anchorage* (LPD-23).
Source: Rader (2017).

Part of HIMARS' success in firing from aboard a ship is its ability to fire with negligible displacement from firing (Oppenheimer, 2013). The potential incorporation of soft recoil technology to wheeled cannons could enable similar employment for Marine Corps howitzers. Also producing little to no recoil, and with only its tires and stabilizers contacting the deck, it is feasible that wheeled cannons could fire from a ship. This potential employment cannot be considered with existing towed howitzers, as their displacement and recoil require that spades be dug in, preventing its use on a flat surface, like a ship deck.

Advancements in unmanned and self-driving vehicles also creates potential for future applications to wheeled artillery. Oshkosh Defense's TerraMax is the unmanned variant of the MTVR, the M777's prime mover (Oshkosh, n.d.). As technology like TerraMax matures, wheeled howitzer alternatives possess the potential to be remotely or autonomously driven as well. Incorporating this technology to a system like ARCHER, which already requires no operator involvement to load or fire, could yield a completely unmanned artillery system. Wheeled systems, such as CAESAR that require manual assistance to load, would require some modifications to its loading system before becoming completely unmanned. This potential incorporation of automation, or remote operation, is obviously not a possibility for any towed howitzer, as detaching and emplacing the howitzer requires significant manual assistance.

In all, the wheeled howitzer platforms present a greater breadth of possibilities for future technology applications. A wheeled howitzer’s combination of vehicle and cannon allows for a wider application of emerging technology. A towed howitzer, with its physical restrictions and dependence on the user, limits the extent that new technologies can be applied. Given the rapidly changing technology in the military, it is prudent to consider the flexibility and adaptability of each alternative.

V. CONCLUSIONS AND RECOMMENDATIONS

The results of this analysis have implications that extend well beyond a decision of which system to buy. At the crux of this study's results is a doctrinal dilemma between improving firepower and remaining transportable. The Marine Corps Operating Concept states the importance of both, but its overall theme emphasizes the need for agility, mobility, and transportability (United States Marine Corps, 2016). The number of constraints that expeditionary requirements impose overwhelmingly influences the selection of alternatives. As a result, the analysis suggests that the Hawkeye, a highly mobile and transportable cannon, is the best alternative, despite a considerably shorter range (see Table 22).

Table 22. Analysis of Alternative Ranking

Alternative Ranking	
1	Hawkeye
2	CAESAR
3	BRUTUS-ER
4	ARCHER
5	BRUTUS
6	M777-ER
7	M777

A notable takeaway from the analysis is the overwhelming performance of wheeled alternatives over the two towed systems. The M777 and other towed artillery systems certainly have their advantages, as demonstrated through decades of successful employment in the U.S. military around the world. Those successes, however, appear to have waned in the face of a more robust and responsive enemy. This analysis suggests that the way forward is with a wheeled howitzer instead of an improved towed system.

The Hawkeye outperformed the other alternatives in every scenario, even when range was considered the only important factor. The combination of its numerous other advantages outweigh its one glaring weakness. Despite the numerical results, this outcome is a difficult course of action to accept. Decision makers are not likely to select a system that not only fails to address the primary concern of range, but actually regresses in that regard.

The Hawkeye does, however, appeal to the expeditionary nature of the Marine Corps. The ability to fit more systems on a single surface connector, its rapid mobility, its high rate of fire, and its vertical lift capability are among the factors that make up for the lack of range. If the Marine Corps wants a truly expeditionary system, able to rapidly follow and support maneuver forces across the battlefield, the Hawkeye is the answer.

The fire support triad, employed from 2009 to 2017, attempted to fill this expeditionary niche through the EFSS. While the EFSS failed to fulfill these needs, the concept of a mixed arsenal, like the fire support triad, should not be considered a flawed concept. The triad received considerable praise for its ability to provide tailorable fire support assets to any given mission. The array of missions that Marine Corps forces face remains too broad to be supported by a single fire support system, and having an arsenal with multiple options proves prudent. By updating the fire support triad concept, the Hawkeye can potentially fill the role previously occupied by the EFSS.

Ultimately, Marine Corps artillery cannot have all of the desired characteristics in a single platform. With the current technologies and systems, the tradeoff between performance and transportability prevents a single alternative from achieving all requirements. Until longer range can be achieved with less weight, this tradeoff is likely to persist. In the meantime, continuing with a mixed arsenal concept, and employing an improved version of the fire support triad with the Hawkeye, presents the means for supporting the MAGTF in the future.

A. RECOMMENDATIONS

Based upon the results of the analysis and the literature review's findings, the following recommendations are advised for the Marine Corps to consider with regard to a wheeled howitzer.

1. The Marine Corps should continue the search for a self-propelled artillery system to replace the M777, as towed artillery systems are not well suited for the future threat environment.

2. The Marine Corps should clearly identify requirements and design characteristics for a replacement of the M777.

3. Hawkeye, or a system of similar design and size, should be among the top considerations for a wheeled howitzer in the Marine Corps. Based on many of Hawkeye's advantages being derived from its size and mobility, the concept of a rocket launcher, mounted on a similar sized platform, is also worth consideration. A miniature version of HIMARS, or a platform similar to the Russian BM-21, could potentially provide the same benefits of Hawkeye, but with a longer range.

4. Given the increased counterbattery threat environment and the proliferation of advanced artillery systems throughout the world, Marine artillery should not be inserted by air unless the system is capable of independent mobility.

5. Artillery systems should either be completely transportable by vertical lift, or size and weight restrictions should only be limited to that of an LCAC. A system that is only partially transportable by vertical lift, such as the M777 serves little purpose in the future threat environment. Without the constraints of vertical lift, systems can be assumed to transit by surface connector and can therefore incorporate any necessary capabilities, unbounded by size or weight.

6. The Marine Corps should continue to employ the concept of the mixed arsenal, and possess multiple artillery systems. Due to the various mission sets faced by the Marine Corps, having the ability to employ the appropriate weapon system for each mission is an invaluable benefit.

7. The Marine Corps should continue to pursue long-range fire support technologies, to include 155 mm and 105 mm ammunition, 155 mm and 105 mm cannon tubes, and various rocket systems.

8. Until the M777 is replaced with an independently mobile artillery system, training and readiness standards should place greater emphasis on decreasing emplacement and displacement times, as well as increased use of survivability moves.

B. FURTHER RESEARCH

Due to the scope of this analysis, some areas of research went unaddressed. Further research to address these areas is recommended. The following are recommendations for extensions and adaptations of this analysis. For access to the documents and tools used in the analysis, contact the author.

1. Employ a survey of decision makers and members of the artillery community, in order to validate and assess requirements and design characteristics. Using this survey data, repeat this analysis format and determine the results.

2. Conduct an extension of this analysis, incorporating a cost analysis and estimate for the various alternatives.

3. Explore the feasibility of wheeled howitzers firing from ship decks, particularly for the discussed alternatives.

4. Modeling the various alternatives in a simulation to provide a more critical assessment of each system’s mission effectiveness.

APPENDIX A. ARTILLERY CONCEPTS AND TERMINOLOGY

A. FIELD ARTILLERY

Field artillery consists of those artillery weapons that are mobile and capable of supporting ground forces in the field. This ability to move and support ground forces differentiates it from other types of artillery, such as coastal artillery or air defense artillery (Dullum et al., 2017; McKenney, 2007). Traditionally, field artillery consists of cannons, known as howitzers. The purpose of the howitzer is to fire projectiles in an indirect manner, which means that the weapon does not aim at the target itself when employed (United States Marine Corps, 2002). Since their advent, land-fired rockets and missiles are also classified as field artillery. Howitzers fire projectiles that receive their thrust from the action of the cannon firing, whereas rockets and missiles are propelled by onboard rockets used after leaving the launcher (Dullum et al., 2017; McKenney, 2007). Most concepts and terminology refer to cannon artillery, but in fact apply across the entire artillery community.

B. CALIBER

Howitzers are often categorized by the size of the caliber it employs. Referring to the diameter of the cannon's bore and its ammunition, a system's caliber is categorized as either light, medium, and heavy artillery (Dullum et al., 2017; United States Marine Corps, 2002). Caliber also refers to the length of the cannon's tube (United States Marine Corps, 2002). In this regard, the caliber is the tube's length divided by the diameter of the bore (United States Marine Corps, 2002). Because of this, two cannons may fire a projectile with the same diameter, but have different calibers. This is due to the different length of each cannon's tube. The diameter of the bore is generally given by a number followed by millimeters or inches, and the length is given by the number followed by the word caliber (i.e., the U.S. M777 is a 155 mm/39 caliber cannon. The 155 mm indicates the diameter of the cannon bore and the projectile, while the 39 refers to the cannon's length).

C. TOWED, TRACKED, AND WHEELED ARTILLERY

Whether a howitzer or a rocket launcher, artillery systems must be able to move around the battlefield in order to support maneuvering ground forces. When the weapon is towed behind a separate vehicle, known as the prime mover, it is referred to as towed artillery, the preponderance of which is employed the cannon as a wheeled trailer (Dullum et al., 2017; McKenney, 2007; United States Marine Corps, 2002). Similarly, when a cannon is mounted onto an independently mobile platform it is known as self-propelled artillery (McKenney, 2007; United States Marine Corps, 2002). Within self-propelled artillery there is another distinction between tracked and wheeled platforms. It is implied that towed systems are wheeled, and are referred to as towed artillery. For the purposes of this study, the term wheeled artillery refers to wheeled self-propelled artillery.

D. EMPLACEMENT AND DISPLACEMENT

In order to provide maximum fire support to advancing maneuver units, artillery units often must move in order to stay within range of targets. While artillery has a relatively long range, it must remain close enough to fire beyond the supported unit's location, to where the enemy is located. Fast-moving units, such as mechanized infantry, tanks, and LAR compound this concern, as artillery must then conduct numerous, rapid movements in order to keep up and provide adequate fire support (United States Marine Corps, 2002). With each move the artillery unit must displace from its position, transit to a new location for future support, and then emplace there. The distance of these movements varies based on the given situation, but one-third of the system's maximum range is a general guideline (United States Marine Corps, 2002). This time-consuming process, when repeated numerous times over a battle, results in less time that artillery coverage is actually provided. To best support maneuver units, artillery units must be capable of displacing, transiting, and emplacing rapidly.

E. SURVIVABILITY MOVES AND EMERGENCY DISPLACEMENTS

Survivability is of critical importance to artillery, and it is aided by the ability to rapidly displace and transit (Dullum et al., 2017). Artillery units face a survivability challenge given the array audible, electronic, and thermal signatures, that they generate

(United States Marine Corps, 2002). Additionally, artillery units often require a considerable amount of large equipment, making it visually observable and difficult to conceal. Even when concealed and omitting minimal signatures, enemy counterbattery radar is capable of detecting fired rounds, identifying the exact location from where the round was originated (United States Marine Corps, 2002). With these various means of detection, artillery units must be capable of rapidly moving (Dullum et al., 2017). Survivability moves are often shorter in distance and are particularly prudent after omitting signatures during firing (United States Marine Corps, 2002). Artillery units routinely conduct survivability moves in order avoid detection, even when they have not fired (United States Marine Corps, 2002). In the event that a unit is detected and subsequently fired upon, it must be able to rapidly displace to avoid damage and casualties; this is known as an emergency displacement (United States Marine Corps, 2002).

F. EMERGENCY OCCUPATIONS

Just as the ability to displace and transit is important, rapid emplacement is vital to artillery's ability to provide continuous fire support. Calls for fire can come at any time, including during a movement to a new position (Dullum et al., 2017). When this occurs, the artillery unit must quickly identify a firing position, emplace, fire the mission, displace, and continue its movement. Known as emergency occupations, these rapid emplacements enable the artillery unit to support units at any given point in a battle (United States Marine Corps, 2002). Moving locations should not impede an artillery unit's ability to provide fire support more than necessary. This is aided by rapid emplacement (Dullum et al., 2017).

G. ADVANTAGES OF INCREASED RANGE

Artillery range has considerable implications for employment in support of ground forces. A greater range is one means of reducing the number of movements required to keep up with maneuver forces. If artillery is capable of sufficiently ranging beyond the maneuver unit, then the artillery unit gains flexibility in timing movements, and can avoid transit in the middle operations (United States Marine Corps, 2002). Greater range also enables firing with a more standoff from the target. It is considerably lower risk to shoot a target when it is incapable of returning fire. In turn, this can reduce the frequency of survivability moves. Conversely, without the ability to fire at long ranges, a unit must operate within the enemy's range just to gain parity, increasing the risk to that unit.

H. RATE OF FIRE

Rate of fire, or the speed at which a weapon is capable of firing, greatly contributes to an artillery system's overall effectiveness. When massing, or concentrating firepower, the quantity of rounds that can be put on the target is paramount (United States Marine Corps, 2002). Systems capable of firing more rounds in a given time can place that much more fire power onto a target. Increasing the rate of fire can result in fewer systems required to achieve the same amount of firepower. The result is that single cannons can generate the same capability that previously would have required entire units. This enables units to disperse their firepower, support more targets, and increasing lethality.

I. MULTIPLE ROUND SIMULTANEOUS IMPACT

Increasing the rate of fire allows for the ability to conduct multiple round simultaneous impact (MRSI) missions (Foss, 2009b). The nature of indirect fire enables howitzers to fire upon the same target using a combination of various trajectories and amounts of propellant. Each combination results in a different time for the round to reach its target, known as time of flight (United States Marine Corps, 2002). Combining high rates of fire with the variations in time of flight, it is possible to fire multiple different trajectories in rapid succession, resulting in all of the rounds landing on the same target simultaneously (Dullum et al., 2017; Turbé, 2010). Some modern systems, like the BAE ARCHER, enable one gun to conduct a MRSI mission with six rounds simultaneously striking one target (Jane's by IHS Markit, 2018e). This MRSI mission capability means that a single howitzer can fire the same number of rounds previously achieved by a whole unit (Turbé, 2010).

J. THE ROLE OF AUTOMATION

The increased rate of fire, and subsequent ability to conduct MRSI missions is largely made possible by increasingly automated systems (Dullum et al., 2017). Manually controlled cannon tubes require a cannoneer to raise and lower the cannon by turning a wheel by hand. Similarly, manually loaded cannons require cannoneers to open the breach, load and ram the projectile, load propellant, and close the breach by hand (Jane's by IHS Markit, 2018o). High angle trajectories make this even more burdensome, as rounds must still be loaded with the tube in the lower position (United States Marine Corps, 2007). This process of repeatedly lowering from a high angle trajectory, loading a round by hand, and raising back to a high angle trajectory is time consuming, and eliminates the possibility of conducting a MRSI mission. Instead, automated howitzers can load rounds faster, and are not constrained by the manual raising and lowering of the tube, enabling high rates of fire.

K. ADVANCED AMMUNITION

The use of improved artillery munitions are one way to increase range and precision. Standard artillery rounds are propelled only by the power of the cannon's explosion, without any further thrust or corrections after leaving the cannon. Rocket assisted projectile (RAP) rounds provide the same capability as standard projectiles, however, an on-board rocket provides additional thrust along the trajectory, extending the round's range (Dullum et al., 2017; United States Marine Corps, 2002). Another special munition in the U.S. inventory is a GPS-guided round capable of correcting course mid-flight, known as Excalibur (Dastrup, 2018). Fins affixed to the round correct the projectile's course mid-flight and guide it to a programmed GPS grid. This guidance capability adjusts for factors that may have moved the round off of its originally intended trajectory, thereby making it more accurate (Dastrup, 2018). The fins also make the round more aerodynamic, giving Excalibur an increased range (Dastrup, 2018). While there are a litany of other ammunition developments, RAP, Excalibur, and comparable extended-range and precision munitions, provide the greatest advancement in artillery ammunition.

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APPENDIX B. WORLDWIDE ARTILLERY CAPABILITIES

Platform	Primary User	Type	Armament	Caliber	Max Range - GPS guided/special ammunition (m)	Max Range - Rocket assisted ammunition (m)	Max Range - unassisted ammunition (m)	Emplacement Time (sec)	Displacement Time (sec)	Rapid Rate of Fire (rds/min)	Susustained Rate of Fire (rds/min)	MRSI (rds)	Traverse (degrees)	Cross Country Speed (mph)	Road Speed (mph)	Combat Load (rds)	Crew Size	Crew Fires From Cover	Armor	Weight (lbs)	Transport Length (Inches)	Transport Width (Inches)	Transport Height (Inches)	Driving Range (miles)	Citation
M777A2	US Marine Corps and US Army	Towed	155 mm	39	40,000	30,000	24,700	180	120	4	2	-	46	-	55	No	7	-	-	9,100	385.2	101.9	105.8	-	(Jane's by IHS Markit, 2018o)
M777A2 with MTVR	US Marine Corps	Towed	155 mm	39	40,000	30,000	24,700	180	120	4	2	-	46	-	60	No	7	-	-	37,000	701.2	101.9	140	30	(Jane's by IHS Markit, 2018o) (Oshkosh Defense, 2014)
M777-ER	US Marine Corps and US Army (Concept)	Towed	155 mm	55	-	70,000	30,000	-	-	-	-	-	-	-	-	No	-	-	-	10,100	479.7	101.9	105.8	-	(Jane's by IHS Markit, 2018o) (Wasserbly, 2017)
M777-ER with MTVR	US Marine Corps	Towed	155 mm	55	-	70,000	30,000	-	-	-	-	-	-	-	60	No	-	-	-	38,000	795.7	101.9	140	300	(Jane's by IHS Markit, 2018o) (Oshkosh Defense, 2014) (Wasserbly, 2017)
MRUTUS	US Marine Corps (Concept)	Wheeled SP	156 mm	39	40,000	30,000	24,700	60	30	4	2	-	-	-	60	-	-	-	-	37,000	385.2	101.9	174	300	(Jane's by IHS Markit, 2018o) (Oshkosh Defense, 2014) (Wasserbly, 2017)
MRUTUS-ER	US Marine Corps (Concept)	Wheeled SP	157 mm	55	-	70,000	30,000	60	30	4	2	-	-	-	60	-	-	-	-	38,000	479.7	101.9	174	300	(Jane's by IHS Markit, 2018o) (Oshkosh Defense, 2014) (Wasserbly, 2017)
M142 HIMARS	US Marine Corps and US Army	Wheeled Rocket	227 mm	-	70,000	-	-	-	-	-	-	-	-	-	58	6	3	Yes	Yes	34,993	305.7	94.5	114.6	300	(Jane's by IHS Markit, 2018n)
EFSS	US Marine Corps (Retired)	Towed Mortar	120 mm	-	17,000	12,500	8,100	60	-	16	4	-	-	-	-	No	-	-	-	-	-	-	-	-	(Jane's by IHS Markit, 2017d)
M119A2	US Army	Towed	105 mm	-	-	19,000	14,000	-	-	8	3	-	360	-	-	No	-	-	-	4,268	-	70.1	53.9	-	(Jane's by IHS Markit, 2018m)
Hawkeye [on HMMWV M1152A1]	US Marine Corps and US Army (Concept)	Wheeled SP	105 mm	-	-	19,000	14,000	60	30	8	3	-	360	-	70	-	-	-	-	12,100	194	87	76	250	(Cox, 2017) (Jane's by IHS Markit, 2018m) (Jane's by IHS Markit, n.d-b)
M109A7	US Army	Tracked SP	155 mm	39	40,500	-	-	60	-	-	-	-	360	-	38	-	4	Yes	Yes	80,000	382	154	129	186	(BAE Systems United States, n.d.) (Jane's by IHS Markit, 2008l)
M198	US Marine Corps and US Army (Retired)	Towed	155 mm	39	-	30,000	22,000	-	-	-	-	-	45	-	45	No	11	-	-	15,791	485.8	110	114.2	-	(Jane's by IHS Markit, 2016)
AS-90	UK	Tracked SP	155 mm	39	-	-	30,000	-	-	6	2	-	360	-	34	48	5	Yes	Yes	99,208	389.8	133.9	118.1	230	(Jane's by IHS Markit, 2017b)
PzH2000	Germany	Tracked SP	155 mm	52	56,000	40,000	30,000	-	-	3 rds/9 sec	10	5	360	-	37	60	5	Yes	Yes	121,981	459.4	140.9	136.2	261	(Jane's by IHS Markit, 2017m)
ATMOS 2000	Israel	Wheeled SP	155 mm	52	-	-	41,000	60	60	9	4	-	50	19	50	27	6	Yes	Yes	46,297	374	98.4	-	621	(Jane's by IHS Markit, 2018d)
G-6	South Africa	Wheeled SP	155 mm	45	38,000	53,600	31,000	60	30	3	2	-	90	19	53	45	6	Yes	Yes	103,617	406.9	133.9	149.6	435	(Jane's by IHS Markit, 2017c)
ARCHER	Sweden	Wheeled SP	155 mm	52	50,000	-	40,000	20	20	9 rds/min 3 rds/20sec	-	6	170	-	43	21	3	Yes	Yes	74,957	563	118.1	129.9	31	(BAE Systems International, n.d.)
CAESAR	France	Wheeled SP	155 mm	52	-	58,000	30,000	35	30	3 rds/15 sec	6	-	34	31	62	18	4	-	-	39,021	391.3	100.4	106.3	373	(Biass, Gander & Gourley, 2001) (Jane's by IHS Markit, 2018p) (Department of the Army, 2014)
K9 Thunder	South Korea	Tracked SP	155 mm	52	-	30,000	18,000	60	-	8	3	-	360	-	62	48	5	Yes	Yes	102,074	472.4	133.9	137.8	234	(Jane's by IHS Markit, 2018h)
EVO-105	South Korea	Wheeled SP	105 mm	34	-	18,000	14,700	-	-	10	3	-	180	-	53	60	5	Partial	-	-	354.3	98.4	126	-	(Jane's by IHS Markit, 2017e)
Taska	Ukraine	Wheeled SP	155 mm	52	-	-	42,000	60	60	3 rds/15 sec	-	-		-	-	16	-	-	-	-	-	-	-	-	(Jane's by IHS Markit, 2017p)
D-30	Russia	Towed	122 mm	-	-	21,900	15,400	90	210	8	4	-	360	16	50	-	7	-	Yes	-	-	-	-	-	(Jane's by IHS Markit, 2017a)
2S1	Russia	Tracked SP	122 mm	-	-	-	15,400	120	60	8	2	-	360	19	37	40	4	-	-	-	-	-	-	311	(Jane's by IHS Markit, n.d.-a)
2S35	Russia	Tracked SP	152 mm	-	-	70,000	40,000	-	-	16	-	Yes	360	-	40	70	3	-	-	-	-	-	-	373	(Army-Technology, n.d.) (Jane's by IHS Markit, 2018a)
2S19	Russia	Tracked SP	152 mm	47	-	29,060	24,700	60-120	60-120	8	4	-	360	16	37	50	5	-	-	-	-	-	-	280	(Jane's by IHS Markit, 2018b) (Departmet of the Army, 2014)
BM-21	Russia	Wheeled Rocket	122 mm	-	-	-	-	150	30	40 rds/20 sec	-	-	181	-	53	40	6	-	-	-	-	-	-	646	(Jane's by IHS Markit, 2018s)
NORINCO SH1	China	Wheeled SP	155 mm	52	-	53,000	32,000	-	-	-	-	-	40	-	56	20	6	Yes	Yes	-	-	-	-	-	(Jane's by IHS Markit, 2017h)
NORINCO SH2	China	Wheeled SP	122 mm	-	-	27,000	15,300	-	-	-	-	-	45	-	56	24	5	Yes	Yes	-	-	-	-	373	(Jane's by IHS Markit, 2017i)
NORINCO SH3	China	Tracked SP	122 mm	-	-	27,000	17,000	-	-	-	-	-	360	-	37	40	5	Yes	Yes	-	-	-	-	311	(Jane's by IHS Markit, 2017j)
NORINCO SH4	China	Wheeled Rocket	122 mm	-	-	27,000	15,300	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(Jane's by IHS Markit, 2017k)
NORINCO SR4	China	Wheeled Rocket	122 mm	-	-	50,000	30,000	300	30	40 rds/30 sec	-	-	-	-	-	40	-	-	-	-	-	-	-	-	(Jane's by IHS Markit, 2017l)
PLZ45	China	Tracked SP	155 mm	45	-	50,000	39,000	-	-	5	2	-	360	-	34	30	5	Yes	Yes	-	-	-	-	-	(Jane's by IHS Markit, 2017f)
PLZ52	China	Tracked SP	155 mm	52	-	58,000	-	-	-	8	-	4	360	-	40	30	4	Yes	Yes	-	-	-	-	280	(Jane's by IHS Markit, 2017g)
Raad-2	Iran	Wheeled SP	155 mm	39	-	34,000	18,100	-	-	4	2	-	360	28	40	30	5	Yes	Yes	-	-	-	-	280	(Jane's by IHS Markit, 2017n)
North Korean Artillery	North Korea	Various	Various	Various	-	-	29,500	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	(Jane's by IHS Markit, n.d-c)

The Worldwide Artillery Capabilities table uses information compiled from multiple sources. The citations for each system are listed in the right-most column, labeled "Citation".

Platform	Type	Weight (lbs)	Transport Length (Inches)	Transport Width (Inches)	Transport Height (Inches)	Transport Speed (MPH)	Driving/Flying Range	Lift Capabbility (lbs)	Citation
HMMWV (M1152A1)	Truck	12,100	194	87	76	70	250 miles	5,000	(AM General, n.d.-b) (Jane's by IHS Markit, n.d.-b)
5 Ton (M1083)	Truck	24,870	286	96	111	60	300 miles	10,000	(Oshkosh Defense, 2015)
7 Ton (M23)	Truck	27,900	316	98	140	65	300 miles	14,199	(Oshkosh Defense, 2014)
MV-22	Tiltrotor	-	290	71	72	246	External: 350 nm	External: 15,000	(Jane's by IHS Markit, 2018f)
CH-53 E	Heavy Helo	-	359	69	78	173	External: 50 nm	External: 32,000	(Jane's by IHS Markit, 2018r)
CH-53 K	Heavy Helo	-	360	108	78	196	External: 110 nm	External: 36,000	(Jane's by IHS Markit, 2017o)
C-130	Cargo Plae	-	480	120	108	-	-	41,790	(Jane's by IHS Markit, 2018k)
C-17	Cargo Plane	-	1056	216	156	-	-	164,900	(Jane's by IHS Markit, 2018g)
LCU 1610	Transport	-	1452	300	-	12.7	1200 nm	254,000	(Jane's by IHS Markit, 2018j)
LCAC	Transport	-	804	324	-	40.3	200 nm	120,000-150,000	(Jane's by IHS Markit, 2018i)
LHA	Ship	-	-	-	-	-	-	None Currently	(Jane's by IHS Markit, 2018c)
LHD	Ship	-	-	-	-	-	-	8 M198, 68 trucks, 3 LCACs or 2 LCUs	(Jane's by IHS Markit, 2018u)
LSD	Ship	-	-	-	-	-	-	4 LCACs, 1-3 LCUs	(Jane's by IHS Markit, 2018v)
LPD	Ship	-	-	-	-	-	-	2 LCACs	(Jane's by IHS Markit, 2018q)

The Worldwide Artillery Capabilities table uses information compiled from multiple sources. The citations for each system are listed in the right-most column, labeled "Citation".

APPENDIX C. SENSITIVITY ANALYSIS DATA

A. MAXIMUM RANGE

Tables 23–28 depict the second iteration of the sensitivity analysis. In this analysis, range is considered the most important requirement, and all other requirements are set equal to one another. This assumption emphasizes the need to overcome the capability gap in firepower.

Table 23. Iteration 2 Pairwise Comparison

Top-Level System Requirements										
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Transportability
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Range
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Range
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Range	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Range	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Rate of Fire	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement

Table 24. Iteration 2 Pairwise Comparison Matrix

Criteria	Criteria	Mobility 1	Transportability 2	Range 3	Rate of Fire 4	Emplacement/Displacement 5	Weights
Mobility	1	1.000	1.000	0.200	1.000	1.000	0.111
Transportability	2	1.000	1.000	0.200	1.000	1.000	0.111
Range	3	5.000	5.000	1.000	5.000	5.000	0.556
Rate of Fire	4	1.000	1.000	0.200	1.000	1.000	0.111
Emplacement/Displacement	5	1.000	1.000	0.200	1.000	1.000	0.111
		0.111	0.111	0.556	0.111	0.111	1.000
							Check

Table 25. Iteration 2 QFD Comparison Matrix

Customer Requirement	Weights	Max Range (km)	Max Rate of Fire (Rds/min)	Max MRSI mission (Rds/Impact)	Time to Emplace (Seconds)	Time to Displace (Seconds)	Driving Speed (MPH)	Independently Mobile (Binary (Yes=1, No=0))	Max Cannons per CH-53E/K (# Cannons)	Max Cannons per LCU (# Cannons)	Max Cannons per LCAC (# Cannons)	
Mobility	0.1111				3	3	5	5				
Transportability	0.1111								5	5	5	
Range	0.5556	5										
Rate of Fire	0.1111		5	3								
Emplacement/Displacement	0.1111				5	5		5				
Check Sum	1.00											
Weighted Performance		2.778	0.556	0.333	0.889	0.889	0.556	1.111	0.556	0.556	0.556	8.8
Performance Percentage		0.316	0.063	0.038	0.101	0.101	0.063	0.127	0.063	0.063	0.063	1.000

Table 26. Iteration 2 Raw Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
Raw Values	Goal	100	10	6	30	30	75	1	1	15	10
	Threshold	70	6	4	75	60	60	1	1	2	2
	M777 w/MTVR	40	4	1	180	120	60	0	1	2	2
	M777-ER w/ MTVR	70	4	1	180	120	60	0	1	2	2
	Haweye	19	8	1	60	30	70	1	1	14	9
	ARCHER	50	9	6	20	20	43.5	1	0	3	1
	CAESAR	58	6	1	35	30	62.1	1	0	6	3
	BRUTUS	40	4	1	60	30	60	1	0	6	3
	BRUTUS-ER	70	4	1	60	30	60	1	0	6	2
	Minimum	10	1	1	240	240	40	0	0	1	1

Table 27. Iteration 2 Normalized Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
10(X-Xmin) (Xmax-Xmin)	Goal	10	10	10	10	10	10	10	10	10	10
	Threshold	7	6	6	8	9	6	10	10	1	1
	M777 w/MTVR	3	3	0	3	6	6	0	10	1	1
	M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1
	Haweye	1	8	0	9	10	9	10	10	9	9
	ARCHER	4	9	10	10	10	1	10	0	1	0
	CAESAR	5	6	0	10	10	6	10	0	4	2
	BRUTUS	3	3	0	9	10	6	10	0	4	2
	BRUTUS-ER	7	3	0	9	10	6	10	0	4	1
	Minimum	0	0	0	0	0	0	0	0	0	0

Table 28. Iteration 2 Weighted Comparison of Alternatives

	Max Range	Max Rate of Fire	Max MRSI mission	Time to Emplace	Time to Displace	Driving Speed	Independently Mobile	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC	
	km	Rds/min	Rds/Impact	Seconds	Seconds	MPH	Binary (Yes=1, No=0)	# Cannons	# Cannons	# Cannons	
Weight	**0.316**	**0.063**	**0.038**	**0.101**	**0.101**	**0.063**	**0.127**	**0.063**	**0.063**	**0.063**	1.000
Normalized Goal (Max)	10	10	10	10	10	10	10	10	10	10	10.000
Normalized Threshold	7	6	6	8	9	6	10	10	1	1	6.729
Normalized Minimum	0	0	0	0	0	0	0	0	0	0	0.000
M777 w/MTVR	3	3	0	3	6	6	0	10	1	1	3.244
M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1	4.299
Haweye	1	8	0	9	10	9	10	10	9	9	6.281
ARCHER	4	9	10	10	10	1	10	0	1	0	5.890
CAESAR	5	6	0	10	10	6	10	0	4	2	6.073
BRUTUS	3	3	0	9	10	6	10	0	4	2	5.141
BRUTUS-ER	7	3	0	9	10	6	10	0	4	1	6.125

B. ALL FACTORS EQUAL

Tables 29–34 depict the third iteration of the sensitivity analysis. In this analysis, all requirements are set equal to one another. This scoring assumes that each requirement is equally important. This was a recommended method of prioritization from PM-TAS (C. Hatch, email to author, September 18, 2018).

Table 29. Iteration 3 Pairwise Comparison

Top-Level System Requirements										
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Transportability
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Range
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Range
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Range	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Range	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Rate of Fire	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement

Table 30. Iteration 3 Pairwise Comparison Matrix

Criteria	Criteria	Mobility 1	Transportability 2	Range 3	Rate of Fire 4	Emplacement/Displacement 5	Weights
Mobility	1	1.000	1.000	1.000	1.000	1.000	0.200
Transportability	2	1.000	1.000	1.000	1.000	1.000	0.200
Range	3	1.000	1.000	1.000	1.000	1.000	0.200
Rate of Fire	4	1.000	1.000	1.000	1.000	1.000	0.200
Emplacement/Displacement	5	1.000	1.000	1.000	1.000	1.000	0.200
		0.200	0.200	0.200	0.200	0.200	1.000
							Check

Table 31. Iteration 3 QFD Comparison Matrix

Customer Requirement	Weights	Max Range (km)	Max Rate of Fire (Rds/min)	Max MRSI mission (Rds/Impact)	Time to Emplace (Seconds)	Time to Displace (Seconds)	Driving Speed (MPH)	Independently Mobile (Binary (Yes=1, No=0))	Max Cannons per CH-53E/K (# Cannons)	Max Cannons per LCU (# Cannons)	Max Cannons per LCAC (# Cannons)	
		Design Characteristics										
Mobility	0.2000				3	3	5	5				
Transportability	0.2000								5	5	5	
Range	0.2000	5										
Rate of Fire	0.2000		5	3								
Emplacement/Displacement	0.2000				5	5		5				
Check Sum	1.00											
Weighted Performance		1.000	1.000	0.600	1.600	1.600	1.000	2.000	1.000	1.000	1.000	11.8
Performance Percentage		0.085	0.085	0.051	0.136	0.136	0.085	0.169	0.085	0.085	0.085	1.000

Table 32. Iteration 3 Raw Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
Raw Values	Goal	100	10	6	30	30	75	1	1	15	10
	Threshold	70	6	4	75	60	60	1	1	2	2
	M777 w/MTVR	40	4	1	180	120	60	0	1	2	2
	M777-ER w/ MTVR	70	4	1	180	120	60	0	1	2	2
	Haweye	19	8	1	60	30	70	1	1	14	9
	ARCHER	50	9	6	20	20	43.5	1	0	3	1
	CAESAR	58	6	1	35	30	62.1	1	0	6	3
	BRUTUS	40	4	1	60	30	60	1	0	6	3
	BRUTUS-ER	70	4	1	60	30	60	1	0	6	2
	Minimum	10	1	1	240	240	40	0	0	1	1

Table 33. Iteration 3 Normalized Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
10(X-Xmin) / (Xmax-Xmin)	Goal	10	10	10	10	10	10	10	10	10	10
	Threshold	7	6	6	8	9	6	10	10	1	1
	M777 w/MTVR	3	3	0	3	6	6	0	10	1	1
	M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1
	Haweye	1	8	0	9	10	9	10	10	9	9
	ARCHER	4	9	10	10	10	1	10	0	1	0
	CAESAR	5	6	0	10	10	6	10	0	4	2
	BRUTUS	3	3	0	9	10	6	10	0	4	2
	BRUTUS-ER	7	3	0	9	10	6	10	0	4	1
	Minimum	0	0	0	0	0	0	0	0	0	0

Table 34. Iteration 3 Weighted Comparison of Alternatives

	Max Range	Max Rate of Fire	Max MRSI mission	Time to Emplace	Time to Displace	Driving Speed	Independently Mobile	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC	
	km	Rds/min	Rds/Impact	Seconds	Seconds	MPH	Binary (Yes=1, No=0)	# Cannons	# Cannons	# Cannons	
Weight	**0.085**	**0.085**	**0.051**	**0.136**	**0.136**	**0.085**	**0.169**	**0.085**	**0.085**	**0.085**	1.000
Normalized Goal (Max)	10	10	10	10	10	10	10	10	10	10	10.000
Normalized Threshold	7	6	6	8	9	6	10	10	1	1	6.750
Normalized Minimum	0	0	0	0	0	0	0	0	0	0	0.000
M777 w/MTVR	3	3	0	3	6	6	0	10	1	1	3.214
M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1	3.496
Haweye	1	8	0	9	10	9	10	10	9	9	8.071
ARCHER	4	9	10	10	10	1	10	0	1	0	6.380
CAESAR	5	6	0	10	10	6	10	0	4	2	6.323
BRUTUS	3	3	0	9	10	6	10	0	4	2	5.753
BRUTUS-ER	7	3	0	9	10	6	10	0	4	1	5.942

C. INCREASED MOBILITY AND DISPLACEMENT/EMPLACEMENT

Tables 35–40 depict the fourth iteration of the sensitivity analysis. In this analysis, the mobility requirement and displacement/emplacement requirement are increased, while all others are set equal. This requirement scoring is suggested by engineers at PM-TAS (C. Hatch, email to author, September 18, 2018).

Table 35. Iteration 4 Pairwise Comparison

Top-Level System Requirements										
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Transportability
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Range
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Range
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Range	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Range	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Rate of Fire	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement

Table 36. Iteration 4 Pairwise Comparison Matrix

Criteria	Criteria	Mobility	Transportability	Range	Rate of Fire	Emplacement/Displacement	
Criteria		1	2	3	4	5	Weights
Mobility	1	1.000	3.000	3.000	3.000	1.000	0.333
Transportability	2	0.333	1.000	1.000	1.000	0.333	0.111
Range	3	0.333	1.000	1.000	1.000	0.333	0.111
Rate of Fire	4	0.333	1.000	1.000	1.000	0.333	0.111
Emplacement/Displacement	5	1.000	3.003	3.003	3.003	1.000	0.333
		0.333	0.111	0.111	0.111	0.333	1.000
							Check

Table 37. Iteration 4 QFD Comparison Matrix

Customer Requirement	Weights	Max Range (km)	Max Rate of Fire (Rds/min)	Max MRSI mission (Rds/Impact)	Time to Emplace (Seconds)	Time to Displace (Seconds)	Driving Speed (MPH)	Independently Mobile (Binary (Yes=1, No=0))	Max Cannons per CH-53E/K (# Cannons)	Max Cannons per LCU (# Cannons)	Max Cannons per LCAC (# Cannons)	
		Design Characteristics										
Mobility	0.3333				3	3	5	5				
Transportability	0.1111								5	5	5	
Range	0.1111	5										
Rate of Fire	0.1111		5	3								
Emplacement/Displacement	0.3335				5	5		5				
Check Sum	1.00											
Weighted Performance		0.555	0.555	0.333	2.667	2.667	1.666	3.334	0.555	0.555	0.555	13.4
Performance Percentage		0.041	0.041	0.025	0.198	0.198	0.124	0.248	0.041	0.041	0.041	1.000

Table 38. Iteration 4 Raw Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
Raw Values	Goal	100	10	6	30	30	75	1	1	15	10
	Threshold	70	6	4	75	60	60	1	1	2	2
	M777 w/MTVR	40	4	1	180	120	60	0	1	2	2
	M777-ER w/ MTVR	70	4	1	180	120	60	0	1	2	2
	Haweye	19	8	1	60	30	70	1	1	14	9
	ARCHER	50	9	6	20	20	43.5	1	0	3	1
	CAESAR	58	6	1	35	30	62.1	1	0	6	3
	BRUTUS	40	4	1	60	30	60	1	0	6	3
	BRUTUS-ER	70	4	1	60	30	60	1	0	6	2
	Minimum	10	1	1	240	240	40	0	0	1	1

Table 39. Iteration 4 Normalized Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
	Goal	10	10	10	10	10	10	10	10	10	10
	Threshold	7	6	6	8	9	6	10	10	1	1
	M777 w/MTVR	3	3	0	3	6	6	0	10	1	1
	M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1
10(X-Xmin) / (Xmax-Xmin)	Haweye	1	8	0	9	10	9	10	10	9	9
	ARCHER	4	9	10	10	10	1	10	0	1	0
	CAESAR	5	6	0	10	10	6	10	0	4	2
	BRUTUS	3	3	0	9	10	6	10	0	4	2
	BRUTUS-ER	7	3	0	9	10	6	10	0	4	1
	Minimum	0	0	0	0	0	0	0	0	0	0

Table 40. Iteration 4 Weighted Comparison of Alternatives

	Max Range	Max Rate of Fire	Max MRSI mission	Time to Emplace	Time to Displace	Driving Speed	Independently Mobile	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC	
	km	Rds/min	Rds/impact	Seconds	Seconds	MPH	Binary (Yes=1, No=0)	# Cannons	# Cannons	# Cannons	
Weight	**0.041**	**0.041**	**0.025**	**0.198**	**0.198**	**0.124**	**0.248**	**0.041**	**0.041**	**0.041**	1.000
Normalized Goal (Max)	10	10	10	10	10	10	10	10	10	10	10.000
Normalized Threshold	7	6	6	8	9	6	10	10	1	1	7.589
Normalized Minimum	0	0	0	0	0	0	0	0	0	0	0.000
M777 w/MTVR	3	3	0	3	6	6	0	10	1	1	3.173
M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1	3.310
Haweye	1	8	0	9	10	9	10	10	9	9	8.753
ARCHER	4	9	10	10	10	1	10	0	1	0	7.618
CAESAR	5	6	0	10	10	6	10	0	4	2	7.872
BRUTUS	3	3	0	9	10	6	10	0	4	2	7.387
BRUTUS-ER	7	3	0	9	10	6	10	0	4	1	7.479

D. TEN FACTORS

Tables 41–46 depict the fifth iteration of the sensitivity analysis. In this analysis, all ten of the original requirements are considered in the analysis. Rather than narrowing the requirements down, all ten of the original points of interest from the sources sought document are incorporated. The scoring the ten requirements is done in a similar manner to the original iteration, relying upon the literature review and guiding documents for justification.

Table 41. Iteration 5 Pairwise Comparison

Top-Level System Requirements										
Mobility	5	4	3	2	1	0.50	**0.33**	0.25	0.20	Transportability
Mobility	5	4	3	2	1	**0.50**	0.33	0.25	0.20	Weight
Mobility	5	4	3	2	1	0.50	**0.33**	0.25	0.20	Range
Mobility	5	4	3	**2**	1	0.50	0.33	0.25	0.20	Rate of Fire
Mobility	5	4	3	2	**1**	0.50	0.33	0.25	0.20	First Round Response
Mobility	5	4	3	2	**1**	0.50	0.33	0.25	0.20	Emplacement/Displacement
Mobility	5	4	**3**	2	1	0.50	0.33	0.25	0.20	Crew Size
Mobility	5	4	3	2	1	**0.50**	0.33	0.25	0.20	Cannon Caliber (bore and length)
Mobility	5	4	**3**	2	1	0.50	0.33	0.25	0.20	Fire Control
Transportability	5	4	**3**	2	1	0.50	0.33	0.25	0.20	Weight
Transportability	5	4	3	2	1	**0.50**	0.33	0.25	0.20	Range
Transportability	5	4	3	**2**	1	0.50	0.33	0.25	0.20	Rate of Fire
Transportability	5	4	**3**	2	1	0.50	0.33	0.25	0.20	First Round Response
Transportability	5	4	3	**2**	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Transportability	5	**4**	3	2	1	0.50	0.33	0.25	0.20	Crew Size
Transportability	5	4	3	**2**	1	0.50	0.33	0.25	0.20	Cannon Caliber (bore and length)
Transportability	5	**4**	3	2	1	0.50	0.33	0.25	0.20	Fire Control
Weight	5	4	3	2	1	**0.50**	0.33	0.25	0.20	Range
Weight	5	4	3	**2**	1	0.50	0.33	0.25	0.20	Rate of Fire
Weight	5	4	**3**	2	1	0.50	0.33	0.25	0.20	First Round Response
Weight	5	4	3	**2**	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Weight	5	4	**3**	2	1	0.50	0.33	0.25	0.20	Crew Size
Weight	5	4	3	2	**1**	0.50	0.33	0.25	0.20	Cannon Caliber (bore and length)
Weight	5	4	**3**	2	1	0.50	0.33	0.25	0.20	Fire Control
Range	5	4	**3**	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Range	5	4	**3**	2	1	0.50	0.33	0.25	0.20	First Round Response
Range	5	4	**3**	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Range	5	**4**	3	2	1	0.50	0.33	0.25	0.20	Crew Size
Range	5	4	3	**2**	1	0.50	0.33	0.25	0.20	Cannon Caliber (bore and length)
Range	5	**4**	3	2	1	0.50	0.33	0.25	0.20	Fire Control
Rate of Fire	5	4	**3**	2	1	0.50	0.33	0.25	0.20	First Round Response
Rate of Fire	5	4	3	2	1	**0.50**	0.33	0.25	0.20	Emplacement/Displacement
Rate of Fire	5	4	**3**	2	1	0.50	0.33	0.25	0.20	Crew Size
Rate of Fire	5	4	3	2	1	**0.50**	0.33	0.25	0.20	Cannon Caliber (bore and length)
Rate of Fire	5	4	3	2	**1**	0.50	0.33	0.25	0.20	Fire Control
First Round Response	5	4	3	2	1	**0.50**	0.33	0.25	0.20	Emplacement/Displacement
First Round Response	5	4	3	**2**	1	0.50	0.33	0.25	0.20	Crew Size
First Round Response	5	4	3	2	1	**0.50**	0.33	0.25	0.20	Cannon Caliber (bore and length)
First Round Response	5	4	3	2	**1**	0.50	0.33	0.25	0.20	Fire Control
Emplacement/Displacement	5	4	**3**	2	1	0.50	0.33	0.25	0.20	Crew Size
Emplacement/Displacement	5	4	**3**	2	1	0.50	0.33	0.25	0.20	Cannon Caliber (bore and length)
Emplacement/Displacement	5	4	**3**	2	1	0.50	0.33	0.25	0.20	Fire Control
Crew Size	5	4	3	2	1	**0.50**	0.33	0.25	0.20	Cannon Caliber (bore and length)
Crew Size	5	4	3	2	**1**	0.50	0.33	0.25	0.20	Fire Control
Cannon Caliber (bore and length)	5	4	3	**2**	1	0.50	0.33	0.25	0.20	Fire Control

Table 42. Iteration 5 Pairwise Comparison Matrix

	Criteria	Mobility	Transportability	Weight	Range	Rate of Fire	First Round Response	Emplacement/Displacement	Crew Size	Cannon Caliber (bore and length)	Fire Control	
Criteria		1	2	3	4	5	6	7	8	9	10	Weights
Mobility	1	1.000	0.333	0.500	0.333	2.000	1.000	1.000	3.000	0.500	3.000	0.0760
Transportability	2	3.000	1.000	3.000	0.500	2.000	3.000	2.000	4.000	2.000	4.000	0.1779
Weight	3	2.000	0.333	1.000	0.500	2.000	3.000	2.000	3.000	1.000	3.000	0.1203
Range	4	3.000	2.000	2.000	1.000	3.000	3.000	3.000	4.000	2.000	4.000	0.2147
Rate of Fire	5	0.500	0.500	0.500	0.333	1.000	3.000	0.500	3.000	0.500	1.000	0.0745
First Round Response	6	1.000	0.333	0.333	0.333	0.333	1.000	0.500	2.000	0.500	1.000	0.0530
Emplacement/Displacement	7	1.000	0.500	0.500	0.333	2.000	2.000	1.000	3.000	3.000	3.000	0.1090
Crew Size	8	0.333	0.250	0.333	0.250	0.333	0.500	0.333	1.000	0.500	1.000	0.0352
Cannon Caliber (bore and length)	9	2.000	0.500	1.000	0.500	2.000	2.000	0.333	2.000	1.000	2.000	0.0966
Fire Control	10	0.333	0.250	0.333	0.250	1.000	1.000	0.333	1.000	0.500	1.000	0.0428
		0.0706	0.1667	0.1053	0.2308	0.0638	0.0513	0.0909	0.0385	0.0870	0.0435	1.0000
												Check

Table 43. Iteration 5 QFD Comparison Matrix

		Design Characteristics										
		Max Range	Max Rate of Fire	Max MRSI mission	Time to Emplace	Time to Displace	Driving Speed	Independently Mobile	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC	
Customer Requirements	Weights	km	Rds/min	Rds/Impact	Seconds	Seconds	MPH	Binary (Yes=1, No=0)	# Cannons	# Cannons	# Cannons	
Mobility	0.0760				3	3	5	5				
Transportability	0.1779								5	5	5	
Weight	0.1203								5	3	3	
Range	0.2147	5										
Rate of Fire	0.0745		5	3								
First Round Response	0.0530											
Emplacement/Displacement	0.1090				5	5		5				
Crew Size	0.0352											
Cannon Caliber (bore and length)	0.0966	5										
Fire Control	0.0428		3		1							
Check Sum	1.00											
Weighted Performance		1.557	0.501	0.223	0.816	0.773	0.380	0.925	1.491	1.250	1.250	9.2
Performance Percentage		0.170	0.055	0.024	0.089	0.084	0.041	0.101	0.163	0.136	0.136	1.000
												Check

Table 44. Iteration 5 Raw Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
Raw Values	Goal	100	10	6	30	30	75	1	1	15	10
	Threshold	70	6	4	75	60	60	1	1	2	2
	M777 w/MTVR	40	4	1	180	120	60	0	1	2	2
	M777-ER w/ MTVR	70	4	1	180	120	60	0	1	2	2
	Haweye	19	8	1	60	30	70	1	1	14	9
	ARCHER	50	9	6	20	20	43.5	1	0	3	1
	CAESAR	58	6	1	35	30	62.1	1	0	6	3
	BRUTUS	40	4	1	60	30	60	1	0	6	3
	BRUTUS-ER	70	4	1	60	30	60	1	0	6	2
	Minimum	10	1	1	240	240	40	0	0	1	1

Table 45. Iteration 5 Normalized Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
10(X-Xmin) (Xmax-Xmin)	Goal	10	10	10	10	10	10	10	10	10	10
	Threshold	7	6	6	8	9	6	10	10	1	1
	M777 w/MTVR	3	3	0	3	6	6	0	10	1	1
	M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1
	Haweye	1	8	0	9	10	9	10	10	9	9
	ARCHER	4	9	10	10	10	1	10	0	1	0
	CAESAR	5	6	0	10	10	6	10	0	4	2
	BRUTUS	3	3	0	9	10	6	10	0	4	2
	BRUTUS-ER	7	3	0	9	10	6	10	0	4	1
	Minimum	0	0	0	0	0	0	0	0	0	0

Table 46. Iteration 5 Weighted Comparison of Alternatives

	Max Range	Max Rate of Fire	Max MRSI mission	Time to Emplace	Time to Displace	Driving Speed	Independently Mobile	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC	
	km	Rds/min	Rds/Impact	Seconds	Seconds	MPH	Binary (Yes=1, No=0)	# Cannons	# Cannons	# Cannons	
Weight	**0.170**	**0.055**	**0.024**	**0.089**	**0.084**	**0.041**	**0.101**	**0.163**	**0.136**	**0.136**	1
Normalized Goal (Max)	10	10	10	10	10	10	10	10	10	10	10
Normalized Threshold	7	6	6	8	9	6	10	10	1	1	6.125768
Normalized Minimum	0	0	0	0	0	0	0	0	0	0	0
M777 w/MTVR	3	3	0	3	6	6	0	10	1	1	3.596869
M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1	4.162892
Haweye	1	8	0	9	10	9	10	10	9	9	7.67125
ARCHER	4	9	10	10	10	1	10	0	1	0	4.545548
CAESAR	5	6	0	10	10	6	10	0	4	2	4.98277
BRUTUS	3	3	0	9	10	6	10	0	4	2	4.39091
BRUTUS-ER	7	3	0	9	10	6	10	0	4	1	4.805381

E. LESS REDUNDANCY/ONLY LCAC

Tables 47–52 depict the sixth iteration of the sensitivity analysis. In this analysis, the original iteration's scoring is used, but redundancy in the QFD is reduced. The overlap between mobility and emplacement/displacement is removed, reducing the impact of those design characteristics. Additionally, redundancy in surface vessel compatibility is reduced by only assessing the number of cannons that can fit on the LCAC, and omitting the LCU.

Table 47. Iteration 6 Pairwise Comparison

Top-Level System Requirements										
Mobility	5	4	3	2	1	0.50	**0.33**	0.25	0.20	Transportability
Mobility	5	4	3	2	1	0.50	**0.33**	0.25	0.20	Range
Mobility	5	4	3	**2**	1	0.50	0.33	0.25	0.20	Rate of Fire
Mobility	5	4	3	2	**1**	0.50	0.33	0.25	0.20	Emplacement/Displacement
Transportability	5	4	3	2	1	**0.50**	0.33	0.25	0.20	Range
Transportability	5	4	3	**2**	1	0.50	0.33	0.25	0.20	Rate of Fire
Transportability	5	4	3	**2**	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Range	5	4	**3**	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Range	5	4	**3**	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Rate of Fire	5	4	3	2	1	**0.50**	0.33	0.25	0.20	Emplacement/Displacement

Table 48. Iteration 6 Pairwise Comparison Matrix

Criteria	Criteria	Mobility	Transportability	Range	Rate of Fire	Emplacement/Displacement	
Criteria		1	2	3	4	5	Weights
Mobility	1	1.000	0.333	0.333	2.000	1.000	0.132
Transportability	2	3.003	1.000	0.500	2.000	2.000	0.250
Range	3	3.000	2.000	1.000	3.000	3.000	0.383
Rate of Fire	4	0.500	0.500	0.333	1.000	0.500	0.095
Emplacement/Displacement	5	1.000	0.500	0.333	2.000	1.000	0.140
		0.1	0.2	0.4	0.1	0.1	1.000
							Check

Table 49. Iteration 6 QFD Comparison Matrix

		Design Characteristics										
		Max Range	Max Rate of Fire	Max MRSI mission	Time to Emplace	Time to Displace	Driving Speed	Independently Mobile	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC	
Customer Requirement	Weights	km	Rds/min	Rds/Impact	Seconds	Seconds	MPH	Binary (Yes=1, No=0)	# Cannons	# Cannons	# Cannons	
Mobility	0.1322						5	5				
Transportability	0.2501								5		5	
Range	0.3829	5										
Rate of Fire	0.0948		5	3								
Emplacement/Displacement	0.1399				5	5						
Check Sum	1.00											
Weighted Performance		1.914	0.474	0.285	0.700	0.700	0.661	0.661	1.251	0.000	1.251	7.9
Performance Percentage		0.242	0.060	0.036	0.089	0.089	0.084	0.084	0.158	0.000	0.158	1.000

Table 50. Iteration 6 Raw Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
Raw Values	Goal	100	10	6	30	30	75	1	1	15	10
	Threshold	70	6	4	75	60	60	1	1	2	2
	M777 w/MTVR	40	4	1	180	120	60	0	1	2	2
	M777-ER w/ MTVR	70	4	1	180	120	60	0	1	2	2
	Haweye	19	8	1	60	30	70	1	1	14	9
	ARCHER	50	9	6	20	20	43.5	1	0	3	1
	CAESAR	58	6	1	35	30	62.1	1	0	6	3
	BRUTUS	40	4	1	60	30	60	1	0	6	3
	BRUTUS-ER	70	4	1	60	30	60	1	0	6	2
	Minimum	10	1	1	240	240	40	0	0	1	1

Table 51. Iteration 6 Normalized Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
10(X-Xmin) / (Xmax-Xmin)	Goal	10	10	10	10	10	10	10	10	10	10
	Threshold	7	6	6	8	9	6	10	10	1	1
	M777 w/MTVR	3	3	0	3	6	6	0	10	1	1
	M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1
	Haweye	1	8	0	9	10	9	10	10	9	9
	ARCHER	4	9	10	10	10	1	10	0	1	0
	CAESAR	5	6	0	10	10	6	10	0	4	2
	BRUTUS	3	3	0	9	10	6	10	0	4	2
	BRUTUS-ER	7	3	0	9	10	6	10	0	4	1
	Minimum	0	0	0	0	0	0	0	0	0	0

Table 52. Iteration 6 Weighted Comparison of Alternatives

	Max Range	Max Rate of Fire	Max MRSI mission	Time to Emplace	Time to Displace	Driving Speed	Independently Mobile	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC	
	km	Rds/min	Rds/Impact	Seconds	Seconds	MPH	Binary (Yes=1, No=0)	# Cannons	# Cannons	# Cannons	
Weight	**0.242**	**0.060**	**0.036**	**0.089**	**0.089**	**0.084**	**0.084**	**0.158**	**0.000**	**0.158**	1.000
Normalized Goal (Max)	10	10	10	10	10	10	10	10	10	10	10.000
Normalized Threshold	7	6	6	8	9	6	10	10	1	1	6.698
Normalized Minimum	0	0	0	0	0	0	0	0	0	0	0.000
M777 w/MTVR	3	3	0	3	6	6	0	10	1	1	4.006
M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1	4.814
Haweye	1	8	0	9	10	9	10	10	9	9	6.902
ARCHER	4	9	10	10	10	1	10	0	1	0	4.749
CAESAR	5	6	0	10	10	6	10	0	4	2	5.096
BRUTUS	3	3	0	9	10	6	10	0	4	2	4.322
BRUTUS-ER	7	3	0	9	10	6	10	0	4	1	4.954

F. LESS REDUNDANCY/ONLY LCU

Tables 53–58 depict the seventh iteration of the sensitivity analysis. In this analysis, the original iteration's scoring is used, but redundancy in the QFD is reduced. The overlap between mobility and emplacement/displacement is removed, reducing the impact of those design characteristics. Additionally, redundancy in surface vessel compatibility is reduced by only assessing the number of cannons that can fit on the LCU, and omitting the LCAC.

Table 53. Iteration 7 Pairwise Comparison

Top-Level System Requirements										
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Transportability
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Range
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Mobility	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Range
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Transportability	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Range	5	4	3	2	1	0.50	0.33	0.25	0.20	Rate of Fire
Range	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement
Rate of Fire	5	4	3	2	1	0.50	0.33	0.25	0.20	Emplacement/Displacement

Table 54. Iteration 7 Pairwise Comparison Matrix

Criteria	Criteria	Mobility	Transportability	Range	Rate of Fire	Emplacement/Displacement	
Criteria		1	2	3	4	5	Weights
Mobility	1	1.000	0.333	0.333	2.000	1.000	0.132
Transportability	2	3.003	1.000	0.500	2.000	2.000	0.250
Range	3	3.000	2.000	1.000	3.000	3.000	0.383
Rate of Fire	4	0.500	0.500	0.333	1.000	0.500	0.095
Emplacement/Displacement	5	1.000	0.500	0.333	2.000	1.000	0.140
		0.1	0.2	0.4	0.1	0.1	1.000
							Check

Table 55. Iteration 7 QFD Comparison Matrix

Customer Requirement	Weights	Max Range	Max Rate of Fire	Max MRSI mission	Time to Emplace	Time to Displace	Driving Speed	Independently Mobile	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC	
		km	Rds/min	Rds/Impact	Seconds	Seconds	MPH	Binary (Yes=1, No=0)	# Cannons	# Cannons	# Cannons	
Mobility	0.1322						5	5				
Transportability	0.2501								5	5		
Range	0.3829	5										
Rate of Fire	0.0948		5	3								
Emplacement/Displacement	0.1399				5	5						
Check Sum	1.00											
Weighted Performance		1.914	0.474	0.285	0.700	0.700	0.661	0.661	1.251	1.251	0.000	7.9
Performance Percentage		0.242	0.060	0.036	0.089	0.089	0.084	0.084	0.158	0.158	0.000	1.000

Table 56. Iteration 7 Raw Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
Raw Values	Goal	100	10	6	30	30	75	1	1	15	10
	Threshold	70	6	4	75	60	60	1	1	2	2
	M777 w/MTVR	40	4	1	180	120	60	0	1	2	2
	M777-ER w/ MTVR	70	4	1	180	120	60	0	1	2	2
	Haweye	19	8	1	60	30	70	1	1	14	9
	ARCHER	50	9	6	20	20	43.5	1	0	3	1
	CAESAR	58	6	1	35	30	62.1	1	0	6	3
	BRUTUS	40	4	1	60	30	60	1	0	6	3
	BRUTUS-ER	70	4	1	60	30	60	1	0	6	2
	Minimum	10	1	1	240	240	40	0	0	1	1

Table 57. Iteration 7 Normalized Capability Values

		Max Range	Max Rate of Fire	Max MRSI Mission	Time to Empalce	Time to Displace	Max Road Speed	Independent Mobility	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC
		km	Rds/Min	Rds/Mission	Seconds	Seconds	MPH	1=Yes, 0=No	# Cannons	# Cannons	# Cannons
10(X-Xmin) (Xmax-Xmin)	Goal	10	10	10	10	10	10	10	10	10	10
	Threshold	7	6	6	8	9	6	10	10	1	1
	M777 w/MTVR	3	3	0	3	6	6	0	10	1	1
	M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1
	Haweye	1	8	0	9	10	9	10	10	9	9
	ARCHER	4	9	10	10	10	1	10	0	1	0
	CAESAR	5	6	0	10	10	6	10	0	4	2
	BRUTUS	3	3	0	9	10	6	10	0	4	2
	BRUTUS-ER	7	3	0	9	10	6	10	0	4	1
	Minimum	0	0	0	0	0	0	0	0	0	0

Table 58. Iteration 7 Weighted Comparison of Alternatives

	Max Range	Max Rate of Fire	Max MRSI mission	Time to Emplace	Time to Displace	Driving Speed	Independently Mobile	Max Cannons per CH-53E/K	Max Cannons per LCU	Max Cannons per LCAC	
	km	Rds/min	Rds/Impact	Seconds	Seconds	MPH	Binary (Yes=1, No=0)	# Cannons	# Cannons	# Cannons	
Weight	**0.242**	**0.060**	**0.036**	**0.089**	**0.089**	**0.084**	**0.084**	**0.158**	**0.158**	**0.000**	1.000
Normalized Goal (Max)	10	10	10	10	10	10	10	10	10	10	10.000
Normalized Threshold	7	6	6	8	9	6	10	10	1	1	6.635
Normalized Minimum	0	0	0	0	0	0	0	0	0	0	0.000
M777 w/MTVR	3	3	0	3	6	6	0	10	1	1	3.943
M777-ER w/ MTVR	7	3	0	3	6	6	0	10	1	1	4.752
Haweye	1	8	0	9	10	9	10	10	9	9	6.965
ARCHER	4	9	10	10	10	1	10	0	1	0	4.976
CAESAR	5	6	0	10	10	6	10	0	4	2	5.310
BRUTUS	3	3	0	9	10	6	10	0	4	2	4.535
BRUTUS-ER	7	3	0	9	10	6	10	0	4	1	5.344

LIST OF REFERENCES

AM General. (n.d.-a). HMMWV Hawkeye. Retrieved June 13, 2018, from http://www.amgeneral.com/our-products-and-services/hmmwv-hawkeye/

AM General. (n.d.-b). M1152 HMMWV—AM General. Retrieved August 8, 2018, from http://www.amgeneral.com/our-products-and-services/m1152/

Army Contracting Command. (2018, February 14). Next generation IBCT/SBCT howitzer. Retrieved from https://www.fbo.gov/index?s=opportunity&mode=form&tab=core&id=8a192dfa01750a790b77711663ec4093

Army Technology. (n.d.). 2S35 Koalitsiya-SV 152mm self-propelled howitzer. Retrieved July 29, 2018, from https://www.army-technology.com/projects/2s35-koalitsiya-sv-152mm-self-propelled-howitzer/

BAE Systems International. (n.d.). ARCHER. Retrieved August 1, 2018, from https://www.baesystems.com/cs/Satellite?c=BAEProduct_C&childpagename=Global%2FBAELayout&cid=1434568506068&packedargs=d%3DDesktop&pagename=GlobalWrapper

BAE Systems United States. (n.d.). M109A7. Retrieved June 14, 2018, from https://www.baesystems.com/en-us/product/m109a7

BBC News. (2014a, July 11). “Rockets” kill soldiers in Ukraine. Retrieved from https://www.bbc.com/news/world-europe-28261737

BBC News. (2014b, July 11). Ukrainian security forces report chronology of latest rebel attacks. Retrieved from https://search.proquest.com/docview/1544273404/abstract/73977C0AD1B24D5BPQ/1

Biass, E., Gander, T., & Gourley, S. (2001). Artillery mainstays—The field howitzers. *Armada International, 25*(4), 2–6. Retrieved from ProQuest

Bonds, T. (2015). *Limiting regret: Building the army we will need* (Report No. CT-437). Retrieved from https://www.rand.org/pubs/testimonies/CT437.html

Bonds, T., Predd, J., Heath, T., Chase, M., Johnson, M., Lostumbo, M., … Steinberg, P. (2017). *What role can land-based, multi-domain anti-access/area denial forces play in deterring or defeating aggression?* (Report No. RR-1820-A). Retrieved from https://doi.org/10.7249/RR1820

Burgess, D. S. (1997). Competing with long-range enemy artillery. *Field Artillery, 1*, 20–24. Retrieved from ProQuest

Butler, M. D. (2012). *The evolution of Marine artillery: A history of versatility and relevance* (USMC Command and Staff College thesis). Retrieved from http://www.dtic.mil/dtic/tr/fulltext/u2/a601031.pdf

Clark, B., & Sloman, J. (2016). *Advancing beyond the beach*. Retrieved from https://csbaonline.org/uploads/documents/CSBA6216-AmphibiousWarfare_FINAL_LoRes.pdf

Clark, J. E. (2003). What is the future of field artillery in the expeditionary warfare environment. *Marine Corps Gazette; Quantico, 87*(6), 14–15. Retrieved from ProQuest

Clem, R. S. (2017). Clearing the fog of war: Public versus official sources and geopolitical storylines in the Russia-Ukraine conflict. *Eurasian Geography and Economics, 58*(6), 592–612. https://doi.org/10.1080/15387216.2018.1424006

Congressional Budget Office. (2016). *The U.S. military's force structure: A primer*. Washington, DC, Retrieved from https://www.cbo.gov/publication/51535

Contreras, C. (2013). U.S. Marines with 1st Battalion, 8th Marine Regiment, 2d Marine Division load a M777 towed 155mm howitzer on to a landing craft air cushion aboard the amphibious assault ship USS Bataan (LHD 5). Retrieved from http://www.defenseimagery.mil/imageRetrieve.action?guid=e1678917c32bedad867b858160d9e59674731f5e&t=2

Cordesman, A. H. (2016). *China military organization and reform.* Retrieved from https://csis-prod.s3.amazonaws.com/s3fs-public/publication/160801_chinese_military_reform.pdf

Cox, M. (2017, September 19). Humvee-mounted howitzer dazzles at modern day Marine. Retrieved from https://www.military.com/defensetech/2017/09/19/humvee-mounted-howitzer-dazzles-modern-day-marine

Cox, M. (2018, July 3). Army quietly begins pounding ISIS in Syria from new fire base. Retrieved from https://www.military.com/daily-news/2018/07/03/army-quietly-begins-pounding-isis-syria-new-fire-base.html

Cranny-Evans, S., Cazalet, M., & Foss, C. F. (2018). The czar of battle: Russian artillery use in Ukraine portends advances. *Jane's International Defence Weekly*. Retrieved from https://janes.ihs.com/Janes/Display/FG_901376-IDR

Dastrup, B. L. (2018). *Artillery strong: Modernizing the field artillery for the 21st century*. Retrieved from https://www.armyupress.army.mil/Portals/7/combat-studies-institute/csi-books/Artillery-Strong-Final.pdf

Defense Acquisition University. (n.d.). Defense acquisition glossary. Retrieved August 20, 2018, from https://www.dau.mil/glossary/

del Mazo, K., & Giorgis, C. (2018). Long live the king. *Marine Corps Gazette, 102*(5), 65–70. Retrieved from ProQuest

Department of Defense. (2004). *Defense acquisition guidebook*. Washington, DC, Retrieved from https://www.dau.mil/tools/dag

Department of Defense. (2015, January 7). *Operation of the defense acquisition system* (DoD Instruction 5000.02). Washington, DC, Retrieved from https://www.dau.mil/guidebooks/Shared%20Documents/DoDI%205000.02.pdf

Department of the Army. (2014). *Worldwide equipment guide, 1: Ground systems.* Retrieved from http://intellibrary.libguides.com/ld.php?content_id=20507709

Department of the Army. (n.d.-a). *Fires center of excellence*. Retrieved October 19, 2018, from http://sill-www.army.mil/

Department of the Army. (n.d.-b). *Illustrated equipment data*. Retrieved from http://www.sas.usace.army.mil/Portals/61/docs/RE/RPXGreensboro/Illustrated_Equipment_Data.pdf

Department of the Navy. (2011, 16 May). *Ship-to-objective maneuver.* Retrieved from https://www.mccdc.marines.mil/Portals/172/Docs/MCCDC/Documents/Concepts/STOM%20May%202011.pdf

Dullum, O. S., Fulmer, K., Jenzen-Jones, N. R., Lincoln-Jones, C., & Palacio, D. (2017). *ARES special report: Indirect fire*. Retrieved from http://armamentresearch.com/ares-special-report-indirect-fire/

Engstrom, J. (2018). *Systems confrontation and system destruction warfare: How the Chinese people's liberation army seeks to wage modern warfare* (Report No. RR-1708-OSD). Retrieved from https://doi.org/10.7249/RR1708

Federation of American Scientists (2000). Landing craft air cushion. Retrieved from https://fas.org/man/DoD-101/sys/ship/lcac.htm

Feickert, A. (2017). *Selected foreign counterparts of U.S. Army ground combat systems and implications for combat operations and modernization* (CRS Report No. R44741) (p. 30). Retrieved from Congressional Research Service website https://fas.org/sgp/crs/weapons/R44741.pdf

Field, W. M. (2004). Marine artillery in the battle of An Nasiriyah. *Marine Corps Gazette, 88*(6), 26–30. Retrieved from ProQuest

Foss, C. F. (2003). Artillery for rapid-reaction forces—Artillery on the move. *Jane's Defence Weekly*. Retrieved from https://janes.ihs.com/DefenceWeekly/Display/1168470

Foss, C. F. (2008). Keeping it wheeled: Self-propelled artillery. *Jane's Defence Weekly*. Retrieved from https://janes.ihs.com/Janes/Display/jdw38452-jdw-2008

Foss, C. F. (2009a). China expands tube artillery capability. *International Defence Review*. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/idr12086-idr-2009

Foss, C. F. (2009b). Drive-by shooting: Self-propelled artillery systems. *Jane's Defence Weekly*. Retrieved from https://janes.ihs.com/Janes/Display/jdw40475-jdw-2009

Foss, C. F. (2014). Roll out: Mapping the appetite for wheeled artillery. *International Defence Review*. Retrieved from https://janes.ihs.com/Janes/Display/idr16695-idr-2014

Foss, C.F. (2018). USMC phases out expeditionary mortar system. *International Defence Review*. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/FG_824787-IDR

Fox, A. C. (2017). The Russian-Ukrainian war: Understanding the dust clouds on the battlefield. *Modern war institute at West Point*. Retrieved from https://mwi.usma.edu/russian-ukrainian-war-understanding-dust-clouds-battlefield/

Gannon, J. (2013). Lighten the MAGTF. *Marine Corps Gazette, 97*(10), 14,16,18-19. Retrieved from ProQuest

Georgiadis, D. R., Mazzuchi, T. A., & Sarkani, S. (2013). Using multi-criteria decision making in analysis of alternatives for selection of enabling technology. *Systems Engineering, 16*(3), 287–303. https://doi.org/10.1002/sys.21233

Gordon, G. P. (2017). TF Spartan and Fire Base Bell. *Marine Corps Gazette, 101*(6), 58–62. Retrieved from ProQuest

Gordon, I. V., Matsumura, J., Atler, A., Boston, S., Boyer, M. E., Lander, N., & Nichols, T. (2015). *Comparing U.S. Army systems with foreign counterparts: Identifying possible capability gaps and insights from other armies* (No. RAN126499). Retrieved from http://www.dtic.mil/docs/citations/ADA617712

Goure, D. (2016, August 19). Will the U.S. Army get serious about revolutionizing long range fires? Retrieved from https://nationalinterest.org/blog/the-buzz/will-the-us-army-get-serious-about-revolutionizing-long-17408

Government Accountability Office. (2008). *Defense acquisitions: Status of the safety, performance, and reliability of the expeditionary fire support system* (GAO-09-189R). Washington, DC: United States Government Accountability Office.

Graf, N. (2014). MTVR 7-ton truck and M777 155mm howitzer. Retrieved from https://www.flickr.com/photos/normangraf/albums/72157649900982819/with/15682401703/

Grau, D. L. W., & Bartles, C. K. (2018). The Russian way of war: Force structure, tactics, and modernization of the Russian ground forces. *The Journal of Slavic Military Studies*, *31*(1), 181–182. https://doi.org/10.1080/13518046.2017.1414732

Harris, M. C. (2017). *Is tube artillery a viable fire support platform for the United States military on the battlefields of the future* (Air War College Thesis). Retrieved from http://www.dtic.mil/dtic/tr/fulltext/u2/1042045.pdf

Hawkes, J. (2016). Rolling out the big guns: Self-propelled artillery developments. *Jane's Defence Weekly*. Retrieved from https://janes.ihs.com/Janes/Display/jdw62861-jdw-2016

Hoerster, F., & Boulet, J. (2004). M777 lightweight howitzer gives the Marine Corps a true expeditionary fire support system. *Marine Corps Gazette; Quantico, 88*(6), 39–41. Retrieved from ProQuest

Jane's by IHS Markit. (2006). U.S. Army orders more ATACMS unitary missiles. Retrieved from https://janes.ihs.com/Janes/Display/jmr70232-jmr-2006

Jane's by IHS Markit. (2016). 155 mm howitzer M198. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaa_0556-jaad

Jane's by IHS Markit. (2017a). 122 mm howitzer D-30. Retrieved from https://janes-ihs-com.libproxy.nps.edu/ArtilleryAirDefence/Display/1501407

Jane's by IHS Markit. (2017b). BAE Systems AS90 (Braveheart) 155 mm self-propelled gun. Retrieved from https://janes.ihs.com/DefenceEquipment/Display/jaa_0455-jaad

Jane's by IHS Markit. (2017c). Denel Land Systems G6 155 mm self-propelled gun-howitzer. Retrieved from https://janes-ihs-com.libproxy.nps.edu/ArtilleryAirDefence/Display/1501357

Jane's by IHS Markit. (2017d). Expeditionary fire support system (EFSS). Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaa_a022-jaad

Jane's by IHS Markit. (2017e). Hanwha Techwin EVO-105 105 mm evolved wheeled self-propelled howitzer. Retrieved from https://janes.ihs.com/Janes/Display/jaad0260-jaad

Jane's by IHS Markit. (2017f). NORINCO 155 mm 45-calibre self-propelled gun-howitzer PLZ45. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaa_0401-jaad#

Jane's by IHS Markit. (2017g). NORINCO 155 mm self-propelled gun howitzer PLZ-05 (PLZ52). Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaa_a120-jaad#

Jane's by IHS Markit. (2017h). NORINCO SH1 155 mm/52-calibre self-propelled artillery system. Retrieved from https://janes-ihs-com.libproxy.nps.edu/ArtilleryAirDefence/Display/1501559

Jane's by IHS Markit. (2017i). NORINCO SH2 122 mm self-propelled artillery system. Retrieved from https://janes-ihs-com.libproxy.nps.edu/ArtilleryAirDefence/Display/1501556

Jane's by IHS Markit. (2017j). NORINCO SH3 122 mm self-propelled howitzer. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaa_a102-jaad#

Jane's by IHS Markit. (2017k). NORINCO SH4 122 mm light-weight self-propelled howitzer. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaad1120-jaad

Jane's by IHS Markit. (2017l). NORINCO SR4 122 mm (40-round) multiple rocket system. Retrieved from https://janes-ihs-com.libproxy.nps.edu/ArtilleryAirDefence/Display/1797351

Jane's by IHS Markit. (2017m). Panzerhaubitze 2000 (PzH 2000). Retrieved from https://janes-ihs-com.libproxy.nps.edu/ArtilleryAirDefence/Display/1501332

Jane's by IHS Markit. (2017n). Raad-2 155 mm self-propelled gun-howitzer. Retrieved from https://janes.ihs.com/Janes/Display/jaa_1269-jaad

Jane's by IHS Markit. (2017o). Sikorsky CH-53K King Stallion. Retrieved from https://janes.ihs.com/Janes/Display/jawaa363-jawa

Jane's by IHS Markit. (2017p). Tasko 155 mm self-propelled howitzer. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaa_a058-jaad

Jane's by IHS Markit. (2018a). 152 mm Koalitsiya - SV (CB) (coalition) self-propelled artillery system. Retrieved from https://janes-ihs-com.libproxy.nps.edu/ArtilleryAirDefence/Display/1764957

Jane’s by IHS Markit. (2018b). 152 mm self-propelled artillery system 2S19 (MTSA-S). Retrieved from https://janes-ihs-com.libproxy.nps.edu/ArtilleryAirDefence/Display/1501333

Jane’s by IHS Markit. (2018c). America class. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jfs_a628-jfs_

Jane’s by IHS Markit. (2018d). ATMOS 2000. Retrieved from https://janes.ihs.com/Janes/Display/jaa_1251-jaad

Jane’s by IHS Markit. (2018e). BAE Systems FH-77 BW L52 Archer (6 × 6) self-propelled artillery system. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaa_0472-jaad

Jane’s by IHS Markit. (2018f). Bell Boeing V-22 Osprey. Retrieved from https://janes.ihs.com/Janes/DisplayFile/JAWA1176

Jane’s by IHS Markit. (2018g). Boeing C-17A Globemaster III. Retrieved from https://janes.ihs.com/Janes/Display/jau_a199-jau_

Jane’s by IHS Markit. (2018h). K9 Thunder. Retrieved from https://janes-ihs-com.libproxy.nps.edu/ArtilleryAirDefence/Display/1501488

Jane’s by IHS Markit. (2018i). Landing craft air cushion. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jfs_3573-jfs_

Jane’s by IHS Markit. (2018j). LCU 1610 class. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jfs_3576-jfs_

Jane’s by IHS Markit. (2018k). Lockheed Martin (Lockheed) C-130 Hercules. Retrieved from https://janes.ihs.com/Janes/Display/jau_1600-jau_

Jane’s by IHS Markit. (2018l). M109A6 155 mm Paladin. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaa_0460-jaad

Jane’s by IHS Markit. (2018m). M119A1/M119A2. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaa_0559-jaad

Jane’s by IHS Markit. (2018n). M142 227 mm (6-round) High-mobility artillery rocket system (HIMARS). Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaa_0662-jaad

Jane’s by IHS Markit. (2018o). M777 155 mm lightweight howitzer. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaa_0550-jaad

Jane’s by IHS Markit. (2018p). NEXTER Systems CAESAR 155 mm SPG. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaa_0465-jaad

Jane's by IHS Markit. (2018q). San Antonio class. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jfs_3566-jfs_

Jane's by IHS Markit. (2018r). Sikorsky S-80 (H-53E) Super Stallion. Retrieved from https://janes.ihs.com/Janes/Display/jau_9161-jau_

Jane's by IHS Markit. (2018s). Splav 122 mm BM-21 MRL family. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jaa_0643-jaad

Jane's by IHS Markit. (2018t). Ukraine—Army. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jwara256-jwar

Jane's by IHS Markit. (2018u). Wasp class. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jfs_3567-jfs_

Jane's by IHS Markit. (2018v). Whidbey Island class. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jfs_4523-jfs_

Jane's by IHS Markit. (n.d.-a). 122 mm self-propelled howitzer 2S1 Gvozdika (M1974). Retrieved from https://janes-ihs-com.libproxy.nps.edu/ArtilleryAirDefence/Display/1501342

Jane's by IHS Markit. (n.d.-b). AM General high mobility multipurpose wheeled vehicle (HMMWV). Retrieved from https://janes.ihs.com/Janes/Display/jmvl0785-jlsu

Jane's by IHS Markit. (n.d.-c). North Korean self-propelled artillery. Retrieved from https://janes.ihs.com/Janes/Display/jaa_0432-jaad

Johnson, A. J., Mogenson, K., Peery, T., Fears, C., & Tate, A. (2011). Marine artillery. *Marine Corps Gazette, 95*(10), 51–55. Retrieved from ProQuest

Johnson, D. (2016). *The challenges of the "now" and their implications for the U.S. Army* (Report No. PE-184-A). Retrieved from https://doi.org/10.7249/PE184

Karber, D. P. A. (2015). *"Lessons learned" from the Russo-Ukrainian war* [Working Paper]. Retrieved from The Potomac Foundation: https://prodev2go.files.wordpress.com/2015/10/rus-ukr-lessons-draft.pdf

Kemp, I. (2007). Howitzers on wheels. *Armada International*, *31(4),* 54,56,58-59. Retrieved from ProQuest

Kofman, M., Migacheva, K., Nichiporuk, B., Radin, A., Tkacheva, O., & Oberholtzer, J. (2017). *Lessons from Russia's operations in Crimea and eastern Ukraine* (Report No. RR-1498-A). Retrieved from https://doi.org/10.7249/RR1498

Kummer, D. W. (2014). *U.S. Marines in Afghanistan, 2001–2009: Anthology and annotated bibliography*. Retrieved from https://www.marines.mil/Portals/59/US%20Marines%20in%20Afghanistan%20Anthology.pdf

Lankford, S. C. (2000). The lightweight howitzer: Only a lightweight solution. *Marine Corps Gazette, 84*(12), 21–24. Retrieved from ProQuest

Lowe, C. (2011, February 20). Marines finally fire their Osprey mortar. Retrieved from https://www.military.com/kitup/2011/02/marines-finally-fire-their-their-osprey-mortar.html

Lowery, N. S. (2011). *U.S. Marines in Afghanistan, 2001–2002: From the sea*. Retrieved from https://permanent.access.gpo.gov/gpo20162/FROM%20THE%20SEA.pdf

Macgregor, D. A. (1997). *Breaking the phalanx: A new design for landpower in the 21st century*. Westport, CT: Praeger.

Mandus Group. (2016, November 4). Hawkeye 105mm integration with HMMWV. Retrieved from http://www.mandusgroup.com/partnering-with-am-general/

Mandus Group. (n.d.). Mandus Group. Retrieved June 13, 2018, from http://www.mandusgroup.com/artillery_solutions/hawkeye_105mm.php

Marine Corps ground modernization in review of the defense authorization request for fiscal year 2019 and the future years defense program: Hearing before the Committee on Armed Services, 115th Cong. (2018). Retrieved from https://www.armed-services.senate.gov/imo/media/doc/18-29_03-20-18.pdf

Maritan, D. (2015). *Practical manual of quality function deployment*. New York, NY: Springer International Publishing. https://doi.org/10.1007/978-3-319-08521-0

Martin, B. (2017). *Amphibious operations in contested environments: Insights from analytic work* (Report No. CT-476). Retrieved from https://doi.org/10.7249/CT476

Matsumura, J., Gordon, J., Steeb, R., Boston, S., Lee, C., Padilla, P., & Parmentola, J. (2017). *Assessing tracked and wheeled vehicles for Australian mounted close combat operations: Lessons learned in recent conflicts, impact of advanced technologies, and system-level implications* (Report No. RR-1834-AUS). Retrieved from https://doi.org/10.7249/RR1834

McKenney, J. E. (2007). *U.S. Army center of military history—Organizational history of field artillery 1775–2003.* Retrieved from https://history.army.mil/html/books/OH_of_FA/index.html

Military Mashup. (n.d.). M777 on LCU. Retrieved from http://militarymashup.com/mmu_get_jpeg.php?0b4f55ddd69d41d26e3861cad51ba873e

Military.com (n.d.). M777 howitzer. Retrieved from https://www.military.com/equipment/m777-howitzer

Mogenson, K., & Tate, A. (2013). Scalable fires capabilities. *Marine Corps Gazette, 97*(11), 94–96. Retrieved from ProQuest

Morrow, P. K. (2011). Analysis of alternatives. Retrieved from https://www.dau.mil/cop/ce/dau%20sponsored%20documents/a3%20analysis%20of%20alternatives%20final.pdf

Navy Supply Corps Newsletter. (2014, February 3). Sailors and Marines load supplies from a landing craft utility (LCU) vehicle into the lower vehicle area of the Austin-class amphibious transport dock ship *USS Denver* (LPD 9). Retrieved from http://scnewsltr.dodlive.mil/files/2015/06/NLI-1.jpg

Office of Aerospace Studies, Air Force Material Command. (2014). *Capabilities-based assessment (CBA) handbook*. Kirtland AFB, NM. Retrieved from https://www.dau.mil/cop/rqmt/DAU%20Sponsored%20Documents/Handbook%20-%20USAF,%20Capabilities-Based%20Assessment%20(CBA),%2010%20Mar%202014.pdf

Oppenheimer, A. (2013). Artillery systems - faster, lighter, stronger. *Military Technology, 37*(7), 12–18. Retrieved from EBSCO

Oshkosh Defense. (2014). MTVR: Medium tactical vehicle replacement. Retrieved from https://oshkoshdefense.com/wp-content/uploads/2016/05/12705_MTVR_bro_single_LoRes_3.2014.pdf

Oshkosh Defense. (2015). FMTV: Family of tactical medium vehicles. Retrieved from https://oshkoshdefense.com/wp-content/uploads/2015/09/17597_FMTV_FamBrch_2015_SnglPgs_LoRes_8.2015.pdf

Oshkosh Defense. (n.d.). TerraMax®. Retrieved October 19, 2018, from https://oshkoshdefense.com/components/terramax/

Pace, J. A. (2005). Myths, misperceptions, and reality of the ground fires triad. *Marine Corps Gazette, 89*(6), 14–17. Retrieved from ProQuest

Potomac Defense Daily. (2009). LW155 impacting way forces fight in Afghanistan. Retrieved from https://search.proquest.com/docview/234071800/abstract/E14A50CD5AB04051PQ/13

Rader, A. (2017). Anchorage conducts HIMARS shoot during Dawn Blitz 2017. Retrieved from https://www.navy.mil/submit/display.asp?story_id=103003

Real Clear Defense. (2018, 4 October). U.S. Army moves closer to commissioning M777ER Howitzer. Retrieved from https://www.realcleardefense.com/2018/10/04/us_army_moves_closer_to_commissioning_m777er_howitzer_304589.html

Report to the Senate and House Appropriations Subcommittees on defense regarding a plan for the utilization of Rock Island Arsenal, 106th Cong. (1999). Retrieved from http://www.dtic.mil/dtic/tr/fulltext/u2/a375183.pdf

Reuters. (2016, December 22). Russian hackers tracked Ukrainian artillery units using Android implant. Retrieved from https://www.reuters.com/article/us-cyber-ukraine/russian-hackers-tracked-ukrainian-artillery-units-using-android-implant-report-idUSKBN14B0CU

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Science, 1*(1), 83–98. https://doi.org/10.1504/IJSCCI.2008.017590

Sadler, W. A. (2000). Caesar: The move, shoot, and scoot artillery system for the 21st century. *Marine Corps Gazette, 84*(12), 29–30. Retrieved from ProQuest

Seck, H. H. (2017a, October 26). Marines want a truck-mounted rocket-launcher that fits in an Osprey. Retrieved from https://www.military.com/defensetech/2017/10/26/marines-want-truck-mounted-rocket-launcher-fits-osprey

Seck, H. H. (2017b, December 19). Marine Corps ditches towed mortar system in push to fund modernization. Retrieved from https://www.military.com/DoDbuzz/2017/12/19/marine-corps-ditches-towed-mortar-system-push-fund-modernization.html

Shanmugam, R. & Chattamvelli, R. (2015). *Statistics for scientists and engineers*. Retrieved from http://ebookcentral.proquest.com/lib/ebook-nps/detail.action?docID=1895998

Szayna, T. S., Bankes, S. C., & Mullins, R. E. (2001). *The emergence of peer competitors: A framework of analysis* (Report No. MR-1346). Retrieved from http://handle.dtic.mil/100.2/ADA398471

Temiz, Y. Z. (2016). *Artillery survivability model* (Master’s thesis). Retrieved from http://hdl.handle.net/10945/49399

Trevithick, J. (2018a, February 16). U.S. Army eyes replacing its 105mm and 155mm towed howitzers with one new cannon. Retrieved from http://www.thedrive.com/the-war-zone/18550/us-army-eyes-replacing-its-105mm-and-155mm-towed-howitzers-with-one-new-cannon

Trevithick, J. (2018b, March 14). Marine Corps is finished with its long-troubled lightweight 120mm mortar systems. Retrieved from http://www.thedrive.com/the-war-zone/19232/marine-corps-is-finished-with-its-long-troubled-lightweight-120mm-mortar-systems

Turbé, G. (2010). The changing world of artillery. *Military Technology, 34*(6), 150–163. Retrieved from EBSCO

U.S. Army. (2016, July 11). Picatinny chrome tubes put to the test. Retrieved from https://www.army.mil/article/171314/picatinny_chrome_tubes_put_to_the_test

United States Marine Corps. (2002). *Artillery operations* (MCWP 3–16.1). Washington, DC, Retrieved from https://www.marines.mil/Portals/59/Publications/MCWP%203-16.1%20Artillery%20Operations.pdf

United States Marine Corps. (2007). *Artillery training and readiness manual* (NAVMC 3500.7). Washington, DC, Retrieved from https://www.marines.mil/Portals/59/Publications/NAVMC%203500.7.pdf

United States Marine Corps. (2010). *U.S. Marine Corps concepts & programs 2010*. Washington, DC, Retrieved from https://www.hqmc.marines.mil/pandr/Concepts-and-Programs/Concepts-and-Programs-2010/

United States Marine Corps. (2016). *Marine Corps operating concept*. Washington, DC, Retrieved from https://www.mccdc.marines.mil/MOC/

United States Marine Corps. (2018). *U.S. Marine Corps concepts & programs 2018*. Washington, DC, Retrieved from http://www.candp.marines.mil/Concepts-Programs-Home/Publication/

United States Naval Institute. (2017, October 24). Marines fire HIMARS from ship in sea control experiment with Navy. Retrieved from https://news.usni.org/2017/10/24/marines-fire-himars-ship-sea-control-experiment-navy

Valpolini, P. (2012). Artillery on wheels. *Armada International, 36(6).* Retrieved from ProQuest

Wasserbly, D. (2017). Picatinny arsenal advances M777 extended range howitzer. *Jane's Defence Weekly*. Retrieved from https://janes-ihs-com.libproxy.nps.edu/Janes/Display/jdw64857-jdw-2017

Woodford, S. (2017, March 29). The Russian artillery strike that spooked the U.S. Army. Retrieved from http://www.dupuyinstitute.org/blog/2017/03/29/the-russian-artillery-strike-that-spooked-the-u-s-army/

Wynes, K., & Bowrey, G. (2013). U.S. 8,468,928 B2. Washington, DC, Patent and Trademark Office. Retrieved from https://patents.google.com/patent/US20120266747

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