Journal of Strategic Security

Volume 9
Number 1 *Designing Danger: Complex Engineering by Violent Non-State Actors*

Article 10

Comparative Analysis of VNSA Complex Engineering Efforts

Gary A. Ackerman
START Center, University of Maryland, ackerman@umd.edu

Recommended Citation

Ackerman, Gary A.. "Comparative Analysis of VNSA Complex Engineering Efforts." *Journal of Strategic Security* 9, no. 1 (2016): 119-133.
DOI: http://dx.doi.org/10.5038/1944-0472.9.1.1511
Available at: http://scholarcommons.usf.edu/jss/vol9/iss1/10

Comparative Analysis of VNSA Complex Engineering Efforts

Author Biography
Dr. Gary A. Ackerman is the Director of the Unconventional Weapons and Technology Division at the National Consortium for the Study of Terrorism and Responses to Terrorism (START). Prior to taking up his current position, he was Research and Special Projects Director at START and before that the Director of the Weapons of Mass Destruction Terrorism Research Program at the Center for Nonproliferation Studies in Monterey, California. His research encompasses various areas relating to terrorism and counterterrorism, including terrorist threat assessment, radicalization, terrorist technologies and motivations for using chemical, biological, radiological, and nuclear (CBRN) weapons, and the modeling and simulation of terrorist behavior. He is the co-editor of Jihadists and Weapons of Mass Destruction (CRC Press, 2009), author of several articles on CBRN terrorism and has testified on terrorist motivations for using nuclear weapons before the Senate Committee on Homeland Security. He completed his PhD in War Studies at King's College London, dealing with the impact of emerging technologies on terrorist decisions relating to weapons adoption.

Abstract
The case studies undertaken in this special issue demonstrate unequivocally that, despite being forced to operate clandestinely and facing the pressures of security forces seeking to hunt them down and neutralize them, at least a subset of violent non-state actors (VNSAs) are capable of some genuinely impressive feats of engineering. At the same time, success in such endeavours is not guaranteed and VNSAs will undoubtedly face a number of obstacles along the way. A comparative analysis of the cases also reveals new insights about the factors influencing the decision to pursue complex engineering efforts, the implementation of such decisions and the determinants of the ultimate outcome. These result in a set of hypotheses and indicators that, if confirmed by future research, can contribute to both operational and strategic intelligence assessments. Overall, the current study enriches our understanding of how and why VNSAs might engage in complex engineering efforts.

Disclaimer
Editor's Note: This article forms part of a series of related case studies collected in this Special Issue and should be viewed in the context of the broader phenomenon of complex engineering by violent non-state actors. Readers are advised to consult the introductory and concluding papers for a full explanation and comparative analysis of the cases.

Acknowledgements
This work was supported by Sandia National Laboratories, Contract #1525332. Any opinions, findings, conclusions and recommendations in this issue are those of the authors and do not necessarily reflect views of Sandia National Laboratories or the U.S. Department of Energy.

Introduction

Close observers – whether in law enforcement, intelligence agencies or academia – of particular terrorist groups and transnational criminal organizations (TCOs) have long been aware of the technical prowess sometimes displayed by their subjects. Yet, those who study violent non-state actors (VNSAs) more broadly, where the relatively straightforward application of firearms, explosives and telecommunications are the overwhelming norm, can sometimes be misled into viewing these exploits as the limit of VNSA capabilities.[1] The preceding cases, however, have demonstrated unequivocally that, despite being forced to operate clandestinely and facing the pressures of security forces seeking to hunt them down and neutralize them, at least a subset of VNSAs have shown themselves to be capable of some genuinely impressive feats of engineering. If these cases (the basic features of which are shown in Table 1) do nothing more than give pause to those who too easily dismiss the potential threats posed by non-state actors, they will have served a useful purpose.

Table 1: Summary of Case Study Features

	PIRA	**Aum Shinrikyo**	**FARC**	**Zetas**	**HAMAS**	***AQ Khan Network***[2]
Complex Engineering Effort	Sophisticated mortar systems	Chemical weapons; Nuclear Weapons	"Narco-subs"	Encrypted countrywide radio network	Operational tunnel network into Israel	*Illicit transfer of nuclear equipment and designs*
Overall Outcome	Successful	Chemical: Limited success; Nuclear: Unsuccessful	Successful	Successful	Successful	*Successful*
Type of Organization	Terrorist	Terrorist / Cult	Terrorist / TCO	TCO	Terrorist	*Smuggling network*
General Motive	Ethnonationalist	Apocalyptic-Millenarian	Marxist; Financial gain	Financial gain	Ethnonationalist; Islamist	*Financial gain*
Regional Context	Western Europe	Asia	South America	North America	Middle East	*International*

[1] For a complete discussion of the literature and theory surrounding complex engineering efforts by VNSAs, as well as the methodology and case selection process, see the Introduction to this Special Issue.
[2] As described in the Introduction to the Special Issue, the AQ Khan network is presented not as a case of complex engineering itself, but rather as an example of how an illicit network might facilitate and support such an effort. It is therefore analyzed separately from the other cases for most purposes in this analysis and is differentiated from the other cases in the table with italics.

Decision

Still, the case studies have a lot more to offer in terms of providing insights into the characteristics that are associated with VNSA complex engineering efforts. Beginning with the decision to engage in complex engineering efforts, Table 2 below summarizes several aspects of the decision making process across the case studies (the A.Q. Khan nuclear case will be discussed separately). For the general context in which decisions were made, in all cases the actual decision to engage in the complex engineering effort was made by the central decision-making body in each organization. Irrespective of who actually carried out the effort, in all cases the organization's senior leadership had to at least give the go-ahead. While there might have been consultation with and input from lower level organizational personnel, it appears that since the effort under consideration represented a major new initiative, requiring the investment of substantial organizational resources and often entailing sizeable risks, it was not left up to functional entities or field commanders to make the key decisions, which occurred in a top-down fashion.

Another common feature across all the cases was the high risk tolerance displayed by the organization's decision makers more generally. While the small number of cases and the absence of negative examples make it difficult to state that a high tolerance for risk is either necessary or sufficient for deciding to engage in a complex engineering effort, it is striking that none of the VNSAs studied could be characterized as being operationally conservative in any way. Moreover, a perceived urgency to act did not seem to color most of the VNSA decision making. While leaders may have perceived a clear strategic need to do something different, in no case (with the exception of Aum Shinrikyo, which had a prophesized deadline only a few years hence) was there evidence that the leaders felt the need to make the decision quickly or rashly. Embarking on a complex engineering effort was therefore mostly a reasoned decision, one that likely estimated the various costs and benefits involved.

Turning to the key question of what factors contributed to the decisions themselves, while the specifics vary considerably across the VNSAs studied, there are several commonalities in the overall motivational formula. This can be discerned by viewing the interacting effects of different levels of motivation that underlie the decision to engage in a complex engineering effort. Across the cases, (1) the basic motivational disposition of the VNSA itself exerts the

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DOI: http://dx.doi.org/10.5038/1944-0472.9.1.1511

broadest stimulus by determining more proximate strategic goals. It is these goals that (2) in turn produce the tactical requirements that (3), often in reaction to external circumstances, then provide the impetus for the organization to make a change in its operations. Lastly, it appears that (4) a variety of contingent and contextual factors influence the selection of a particular solution to the operational problem that involves a complex technology, as well as the decision to engage in an internal engineering effort to obtain this technology. For example, in the case of the PIRA, their fundamentally ethnonationalist conflict against the British pushed them to attack police and military targets, which in turn sparked a search to tactically overcome the high-walled fortifications surrounding these targets, while several contextual factors, including particular tactical requirements in an urban environment and a distrust of externally sourced armaments, led them to pursue their own mortar systems. Similarly, the FARC, which had evolved to pursue financial gain, was driven to make operational changes by increased interdiction rates by counternarcotics authorities, while the advantages in terms of carrying capacity and detection avoidance, together with a high return on investment, prompted the decision to pursue a submersible development program.

Table 2: Decision Characteristics

	PIRA	**Aum Shinrikyo**	**FARC**	**Zetas**	**HAMAS**
Decision Makers	Army Council	Shoko Asahara (leader)	General Secretariat and Joint Western Command	Heriberto Lazcano-Lazcano (with Antonio Cardenas-Guillen, JorgeCostilla-Sanchez)	Al-Qassam Brigades (esp. Mohammed Deif)
Decision Process	Mainly top-down, centralized for mortars (with some bottom-up input)	Extremely top-down, centralized	Top-down (with some bottom-up input from individual fronts)	Top-down	Top-down
General Risk Tolerance	High	Very High	High	High	High
Perceived Urgency	Moderate	High	Low	Low	Low
Motivation for Change	Destroy fortified targets	Overthrow Japanese government and initiate doomsday; leader's fetish-like affinity for unconventional weapons	Counteract improved detection / interdiction efforts by authorities	Better operational coordination and intelligence gathering than rivals	To address military imbalance asymmetrically and penetrate defenses

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Key Drivers of Internal Development of Specific CE	(1) Specific tactical requirements not met by available products (other weapons or military mortars) (2) External sources largely unavailable (3) Distrust of externally sourced material (4) DIY prestige (5) Confidence in technical prowess (6) Allowed for tactical/strategic evolution	(1) Failure to procure weapons from external sources (2) Copious financial resources (3) Confidence in leader's prophecies	(1) Tactical advantages over alternatives in terms of avoiding detection (2) High return on investment (3) Resale / rental opportunities	(1) Existing infrastructure inadequate for its needs (2) Military background of leaders (desire for efficiency and precision) (3) Possessed sufficient resources (cost tens of millions of dollars) (4) Prestige (messaging to rivals; government)	(1) Prior experience in building tunnels (2) Covert penetration of Israel (3) Provide protection (weapons storage and leadership) (4) Provide (busy) work for Hamas members and boost morale (5) Limited tactical support from state sponsors
Long-Term Investment in CE	Yes	Chemical: Somewhat; Nuclear: No	Yes	Yes	Yes

One salient motivational factor to note is that in every case studied, the desire on the part of the VNSA to alter its operational posture was prompted by some change in the VNSA's strategic or tactical environment, whether it is an electoral loss (as in the case of Aum Shinrikyo), or the persistence of multiple rivals in illicit markets (as in the case of the Zetas). It can thus be hypothesized that complex engineering efforts by VNSAs are much less likely to arise spontaneously where an organization perceives itself to be enjoying tactical and strategic success in terms of reaching its immediate goals.

A second hypothesis suggested by the cases is that a complex engineering task is more likely to be undertaken in the absence of any simple alternatives that will solve the operational problem that the VNSA is confronted with. This accords with the general theory that VNSAs tend to be conservative and imitative in their operations and will in most instances pursue the path of least resistance. A corollary to the hypothesis is that a complex technology will usually be sought only if there exists no simple technology that will suffice and that a VNSA will usually decide to engage in an internal engineering effort to acquire the technology only if no external suppliers are readily available or if external supply poses too many security risks.

It also appears that, even though the VNSAs studied were willing to take large risks, they did not undertake complex engineering projects on the off chance that they might be successful. In all the cases studied, leaders seem to have made the final decision to embark on such an effort only if they had at least some degree of confidence in their groups' ability to pull it off. Whether the source of this confidence lay in having copious resources, professional cadre,

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DOI: http://dx.doi.org/10.5038/1944-0472.9.1.1511

prior experience in similar technical areas, or even a delusional faith in prophecy (as in the case of Aum Shinrikyo), the decision was made based on some expectation of success, at least in the long run. Another hypothesis is therefore that a positive decision to pursue a complex engineering effort will be far more likely if factors can be identified that might boost leaders' confidence in their efforts' ultimate success.

In at least two of the cases (the PIRA and Los Zetas), the desire for prestige likely played some role in the decision. Here, the very act of the VNSA undertaking a complex, risky and resource-intensive effort might have been perceived as valuable in terms of messaging to opponents, rivals or followers that the organization was one to be reckoned with. While likely neither to be a necessary nor sufficient criterion, it can thus be hypothesized that where an organization is especially concerned with its image as a sophisticated, innovative actor, a desire for prestige can be a powerful facilitating factor in the decision to engage in a complex engineering effort.

The case studies support many of the broader findings and theories of how and when VNSAs decide to innovate, as outlined in the introductory article. Several of the drivers of innovation mentioned in the literature, such as countermeasures by security forces and a greater desire for status, are reflected in the cases. So is causal variation in the decision making, although the cases of complex engineering efforts presented in this volume point towards a more generalizable decision framework (as described above) than is discernible in the broader VNSA innovation context. The importance placed in the literature on a willingness to take risks and organizational learning is also echoed by the case studies. Another factor is the facilitative effect of internal champions, which is alluded to in several of the cases. However, because the champions in the cases tended to coincide with the senior leadership of the VNSAs, it is not possible to identify an independent effect of internal or external champions.

Factors identified in the literature on VNSA innovation that were not supported (but also not contradicted) by the majority of the case studies were: The effects of demonstration of the technology by other VNSAs[3] on the decision to pursue a complex engineering efforts (since most of the complex engineering efforts had never been undertaken by VNSAs previously), whether a self-sustaining momentum developed that would have continued to drive the efforts even in the absence of the initial stimuli, and the extent to

[3] The Hamas case did reflect this factor, however, in that its ally Hezbollah as well as its rival Fatah had previously constructed tunnels.

which the possession of institutionalized R&D organs or safe havens contributed towards the decision to engage in these efforts. However, related to this last area, possessing high levels of resources seem to be particularly important in the context of the decision to proceed with a complex engineering effort, which would not necessarily be the case with broader VNSA innovation. Given the selection of case studies of only positive decisions to pursue, several findings in the literature, such as the disincentives for innovating in the presence of internal discord or high pressures from security forces, could not be explored in the current study.

Implementation

The case studies make perhaps their greatest contribution with respect to exploring the implementation of complex engineering efforts by VNSAs, given that there is scant existing literature on this topic. Table 3 summarizes the implementation aspects examined across the five relevant cases. First, from the time frames over which implementation occurred, it is immediately apparent that complex engineering tasks are not generally implemented very quickly, at least not to the extent that they return results that can be regarded as unqualified successes. It appears to take a minimum of several years' worth of effort to yield even modestly successful outcomes (as in the cases of Aum's chemical weapons), and can take upwards of a decade or more to achieve the fully-realized outcomes initially envisaged by group leaders (as in the cases of PIRA mortars and FARC "narco-submarines"). It can thus be hypothesized that complex engineering efforts by VNSAs take a considerable amount of time, at least relative to the highly dynamic environment within which most VNSAs operate. If confirmed, this would suggest that law enforcement, intelligence and military agencies have a sizeable window in which to detect and interdict such efforts.

Table 3: Implementation Characteristics

	PIRA	**Aum Shinrikyo**	**FARC**	**Zetas**	**HAMAS**
Time Frame	1970-1990s	Chemical: 1990-1995; Nuclear: 1992-1993	1992-present	2006-2012	Circa 2007-present
Location	Various in Republic of Ireland; also N. Ireland and maybe England	Various facilities in Japan and farm in Australia	Sanquianga and Buenaventura Regions, Colombia	Majority of Mexico's 31 states	Gaza
Primary Implementer	Engineering Department	"Ministry of Construction"; "Ministry of Science and Technology"	Joint Western Command	Technical team (~20 people) led by Jose Estrada; assisted by local plaza bosses	Al-Qassam Brigades Engineering Unit (direction by M. Deif, A. al-Jaabari)

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DOI: http://dx.doi.org/10.5038/1944-0472.9.1.1511

Technical Expertise Needed	Explosives; machining; propulsion / aerodynamics	Chemical engineering; nuclear physics; metallurgy; mechanical engineering	Technical design and construction (e.g., engineers, welders, electricians, fiberglass installers); experts in navigation equipment; experienced seafarers	Telecommunications engineers; hardware / software expertise.	Geology; structural engineering; electrical engineering; mining
Key Source of Expertise	Professionally-trained members (incl. engineers); military manuals & personnel; trial and error	Recruitment of professionally-trained members; outside consultants; the Internet	Professionally-trained members; Colombian navy personnel; subcontractors (Russian, Sri Lankan, Pakistani engineers); coerced naval engineers	Initially, hiring technicians; later, kidnapping and coercion	Prior experience with smuggling tunnels; assistance from Hezbollah (perhaps indirectly Iran and N. Korea)
Key Source of Materials / Equipment	Legitimate purchase; state sponsor (Libya)	Legitimate purchase through front companies	Legitimate purchase (?)	Legitimate purchase by plaza bosses	Illegitimate (Egyptian smuggling tunnels) and legitimate purchase
Collaboration	Limited (high explosives from Libya)	Networks of scientists and officials in Russia, US and elsewhere, often accessed through front companies	Limited (individual subcontractors)	Gulf Cartel (for a time)	Hezbollah; Iran; Gulf states
Concern with Safety	Less concern early period; more concern later (moderate overall)	High	Low	Low	Unknown (likely moderate)
Concern with Security	Low in Rep. of Ireland; High in Northern Ireland and elsewhere	Moderate	High	Moderate	High
Obstacles Encountered	Accuracy; safety; detonation reliability	Lack of access to nuclear materials; design flaws in chemical production and delivery	Design flaws	Government counter-operations; difficult terrain	Detection of building activities; maintenance requirements
Response to Obstacles	Perseverance; technical improvements	Switch from nuclear back to chemical (and biological); increased resource investment to correct design flaws	Perseverance; technical improvements from new expertise	Perseverance - replaced seized / destroyed equipment; expanded infrastructure in rural areas	Perseverance; more inconspicuous methods (e.g., digging by hand); devoted extensive resources to maintenance

Second, and acting to some extent in a countervailing fashion to the previous point about windows of opportunity for law enforcement and intelligence, across all of the cases the complex engineering efforts studied took place in locations wherein the VNSAs could operate in relative security, with a good chance of remaining unmolested. The PIRA enjoyed some degree of sanctuary in the Republic of Ireland while developing their mortars; Aum Shinrikyo was protected by the Japanese government's reticence to scrutinize religious movements and the isolation of their Australian property; FARC conducted its "narco-sub" operations in inaccessible jungle areas; the Zetas enjoyed near impunity in many regions of Mexico where corruption had infested civil society; and Hamas controlled the territory of Gaza when it built its operational tunnels. The existence of VNSA safe havens can therefore be hypothesized to complicate counterterrorist or counter-criminal attempts to detect or interrupt complex engineering efforts.

Third, in terms of who within the VNSA is tasked with implementing the complex engineering effort, in almost all the cases the responsibility was given to a specialist technical or logistical organ in the group, whether this was institutionalized (as in the cases of the PIRA, Hamas, and Aum Shinrikyo) on a broader scale in the organizational structure or more ad-hoc (as in the cases of FARC and the Zetas). Complex engineering efforts by their very nature are highly technical and will almost always represent a radical departure from standard operating procedures within the VNSA. This accords with the more general theory that dedicated, separate R&D organs can bolster the chances of success when VNSAs choose to innovate; indeed, in the context of complex engineering efforts, this might be more of a requirement than a facilitating factor. The existence of a well-resourced, specialized entity endorsed by the leadership might thus be a necessary precondition for any serious attempt to realize a complex engineering effort, which in turn might provide specific, moderately diagnostic indicators[4] for intelligence analysts observing the VNSA.

Fourth, with respect to the types of expertise needed, these vary considerably across cases, although—as is to be expected—various types of engineering (including electrical, aeronautical, chemical, structural and mechanical) feature prominently. Much of the required expertise appears to have come from professionals who had been previously trained, whether this could be found among existing members (as in the PIRA and Hamas cases), members specially recruited for their expertise (as in the case of Aum), hired consultants (in the case of FARC), external actors lending assistance (Hamas), or even coerced technicians (in the cases of FARC and Los Zetas). While there was also some internal development of expertise, for example by sending

[4] Heuer, Richards, *Psychology of Intelligence Analysis* (Langley, VA: Center for the Study of Intelligence, 1999).

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DOI: http://dx.doi.org/10.5038/1944-0472.9.1.1511

members for professional training (PIRA) or a process of trial and error (PIRA and Hamas), it can be hypothesized that in most cases VNSA complex engineering efforts will involve some degree of externally-sourced professional expertise, at least if the organization is keen on keeping the length of the development cycle to a minimum. Thus, contrary to the literature on general VNSA innovation, professional technical expertise, beyond a generally proficient and stable membership, might be necessary. If confirmed, this can provide opportunities for detection of complex engineering activities by VNSAs.

Conversely, when it comes to the source of needed materials, in almost every case at least a significant portion of these materials were purchased from commercial suppliers, albeit often under the pretext of legitimate commerce, e.g., through front companies. While there was some assistance from state sponsors (in the case of Hamas and the PIRA), and some acquisition from illicit networks, in none of the cases studied was there outright theft to obtain materials, which would have provided a useful indicator of activity. If the reliance on legitimate purchase for materials applies more broadly than the cases studied, this potentially makes it more difficult for intelligence and law enforcement agencies to detect most complex engineering efforts through material acquisition activities, unlike the case with, say small arms, explosives and nuclear materials acquisition.

Fifth, although many of the cases involved at least some collaboration with outside entities, except for the professional expertise provided from outside (which generally occurred on an individual basis), it appears as if collaboration with outside actors, such as states or other VNSAs was not entirely necessary. For example, Libya provided the PIRA with high explosives, which certainly assisted in their production of mortars, but even before this, the PIRA had succeeded in creating operational mortars using home-made explosives. Similarly, while Hezbollah may have assisted Hamas in designing attack tunnels, Hamas had decades of internal Palestinian experience with smuggling tunnels to draw upon.

Sixth, organizational concern with the safety of general VNSA members involved in complex engineering efforts is variable across the cases, although it is interesting to note that the only group which unequivocally paid careful attention to its members' safety was Aum Shinrikyo, which was also arguably the least successful of the cases studied in terms of its complex engineering endeavors. This does not necessarily contradict the assertion in the literature that key members with technical skills and experience will be protected, since the cases mostly do not reveal how the safety of these key implementers was regarded within the organization. In the related matter of how much operational security VNSAs employed during their complex engineering efforts, this was generally moderate to high, with the key determinant apparently the degree to which the organization believed itself to be vulnerable to security forces.

The last aspect of implementation and a particularly important one involves the obstacles experienced during the process and how the VNSAs responded to these obstacles. It is immediately apparent from the cases that, as expected, almost any endeavor undertaken by a VNSA that qualifies as a complex engineering effort is almost certain to face at least some obstacles along the path from conception to execution. One assumption, which spans the relevant literature and which applies to all of the obstacles discussed below, is that as the complex engineering task in question becomes more complex and more technically demanding, the potential obstacles become greater in number and severity. While the case studies do not confirm this assumption as such, they certainly do not contradict it either. In every case studied, the VNSA under consideration experienced at least one (and often more) serious impediments to success. These ranged from defects in design (e.g., PIRA and FARC), lack of access to materials (Aum Shinrikyo), operating in difficult terrain (Los Zetas) and having to avoid government forces during implementation (Los Zetas and Hamas).

However, in the case of all but Aum, a common thread amongst the various responses was perseverance in the effort despite setbacks. It was only in the Aum Shinrikyo case of nuclear weapons where the group abandoned their plans and switched back to chemical and biological agents; it might not be coincidental that this is the organization that ultimately enjoyed possibly the least success from a purely engineering point of view. Besides perseverance, the VNSAs employed a variety of means to overcome obstacles, including making iterative technical improvements, bringing on additional expertise, replacing infrastructure lost to security force activity and increasing their resource investment in the project. Each of these, however, can be seen as an adaptation to an internal or external impediment. It can be hypothesized that VNSAs that possess sufficient fortitude to persevere in the face of setbacks and that have the capacity to devote additional resources (including personnel, equipment, and funding) to a complex engineering effort are far more likely to succeed in the face of almost inevitable obstacles. Conversely, those VNSAs who lack suitable depth in motivation and capability are

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DOI: http://dx.doi.org/10.5038/1944-0472.9.1.1511

hypothesized to be far less likely to succeed in complex engineering efforts in general.

Outcome

Most of the cases studied (with the notable exception of Aum's nuclear program) represent successful attempts by VNSAs to engage in complex engineering efforts. Table 4 encapsulates the major factors identified in each case study as being primarily responsible for the outcome of the complex engineering effort. The VNSAs under examination pursued very different types of technology as part of these efforts. Yet, while each case had some unique determinants of success, from the cases as a whole we can identify four key elements that in general might be expected to increase the probability of a VNSA being successful in a complex engineering endeavor.

Table 4: Outcome Summary

Case	Outcome	Main Determinants of Outcome
PIRA	Success	(a) Organizational and individual expertise and access to materials (b) Safe haven (c) Culture of learning
Aum	*Chemical*: Limited Success *Nuclear*: Failure	*Chemical*: (a) High resources (b) Safe haven (protected as a religion under Japanese law) (c) Technical personnel, but insufficiently skilled *Nuclear*: (a) Self-imposed ideological deadline (b) Lack of physics knowledge and practical expertise in nuclear engineering
FARC	Success	(a) Financial and human resources (b) Safe havens (inaccessible areas) (c) Culture of learning / long-term strategy (d) Influence over populace
Zetas	Success	(a) High resources (b) Ruthless efficiency and esprit d'corps
HAMAS	Success	(a) High resource investment (b) Prior experience with smuggling tunnels (c) Culture of Learning
AQ Khan Network	*Success (in terms of smuggling)*	*(a) Unfamiliar environment for intelligence agencies* *(b) Concealment activities* *(c) Venal suppliers* *(d) Lack of political will to prevent activities*

1. *Substantial investment of resources*. The very nature of complex engineering efforts means that they will invariably require significant amounts of both human and financial resources to undertake. This is especially true when one considers the inevitable obstacles that will

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arise during any attempt to operationalize a new, complex process. Not only must a VNSA possess (or be able to acquire) high levels of resources, but it must be both willing and able to devote these resources to the complex engineering effort, most likely maintaining these levels over an extended period of time as the development process matures. In at least four of the five case studies of complex engineering efforts (Aum Shinrikyo, Los Zetas, FARC and Hamas), the VNSAs possessed large amounts of fungible resources that could be applied to the complex engineering effort without detracting significantly from other activities, and even in the case of the PIRA, the leadership was willing to devote a non-negligible proportion of its resources to mortar development for more than two decades. A corollary to this hypothesis is that a long-term commitment is needed for most complex engineering efforts to succeed.

2. *Technical Expertise*. As in the more general case of innovation by VNSAs, the transfer or development of the required technical knowledge and practical skills played a central role in determining outcomes in the case studies.[5] Whether by bringing in outside expertise (e.g., FARC and Los Zetas) or developing their own through trial-and-error (e.g., PIRA and Hamas), it is hypothesized that a VNSA complex engineering effort is unlikely to succeed without acquiring the appropriate amount of technical expertise for the effort at hand. In most respects, there is no place for amateurs in complex engineering efforts. The Aum Shinrikyo case exemplifies this—in the domain in which the group possessed expertise, namely chemical engineering, it was more successful, while in those areas where this expertise was lacking, namely nuclear physics and nuclear engineering, it failed miserably, despite the devotion of substantial resources and efforts in that direction.

[5] A more nuanced approach to this topic is to focus separately on the different knowledge components embodied in technical skills. These can be separated into what Michael Kenney characterizes as general technical knowledge (*techne*) and contextual, experiential knowledge (*mētis*), both of which are argued to be crucial to successful adoption of new technology. Kenney, Michael, " 'Dumb' Yet Deadly: Local Knowledge and Poor Tradecraft Among Islamist Militants in Britain and Spain," *Studies in Conflict & Terrorism*, 33:10 (2010), 911-932; Ackerman, Gary, "'More Bang for the Buck': Examining the Determinants of Terrorist Adoption of New Weapons Technologies" (PhD Dissertation: King's College London, 2014), 23, available at: *https://kclpure.kcl.ac.uk/portal/files/32901277/2014_Ackerman_Gary_0715371_ethesis.pdf,* 87-90.

http://scholarcommons.usf.edu/jss/vol9/iss1/10
DOI: http://dx.doi.org/10.5038/1944-0472.9.1.1511

3. *Safe haven*. As noted above, one feature shared by nearly all of the VNSAs studied was that they were able to pursue their complex engineering efforts over extended periods in circumstances where direct engagement with security forces was unlikely. They were able to engage in R&D in a relatively secure environment with relatively little operational risk. A plausible hypothesis is thus that some measure of safe haven is necessary for most VNSAs' complex engineering efforts to succeed.

4. *Culture of learning*. The last factor that seems to have played an important role in more than one case is the ability of the VNSA to identify the source of deficiencies in its efforts, and then to persevere until a solution to the problem is found and executed. This ties into the investment of resources in that it implies commitment to the effort over an extended period of time.

It is at this stage that reference to the A.Q. Khan case study can be made. The relevance of this case lies in how it demonstrates that VNSAs need not depend on state actors for even the most highly technical and difficult to obtain components and expertise required for complex engineering efforts. Driven by the opportunity for financial gain, A.Q. Khan stood at the head of an illicit non-state actor network that persisted for over fifteen years and spanned more than twenty countries around the world. Although the Khan network was provided with some cover by the Pakistani state, even when this diminished, the network endured despite extensive nonproliferation efforts by the major powers following the fall of the Soviet Union in the early 1990s. Two of the main reasons for the continued success of A.Q. Khan in providing nuclear equipment and expertise to a variety of customers (fortunately, none of them non-state actors) were the willingness of legitimate suppliers to look the other way in exchange for increased profit and the ability of the network to move further up the supply chain to obtain more basic components that were not controlled. Nor was the Khan case an anomaly. While it illustrates that an illicit trading network could exist for even the most dangerous and sophisticated technology, there are many other instances of non-state actor networks supplying dangerous materials for profit, including the long-standing arms smuggling networks of Viktor Bout and Monzer Al-Kasser and the biological agent exploits of Wouter Basson, the former head of the South African chemical and biological weapons programs, who also "went rogue" while enjoying the tacit protection of the state.

Future Research Directions and Policy Implications

The case studies have provided several insights into the decision, implementation and outcomes of complex engineering efforts as undertaken by VNSAs. The observation that we are able to discern several common elements—from similar decisional underpinnings to factors that facilitate implementation—across very different cases reflecting different time periods, geographic regions and motivations, indicates that VNSA complex engineering efforts might be shaped by similar dynamics and subject to a particular set of constraints. However, as noted in the introductory article to the special issue, the case studies represent only an exploratory investigation into the phenomenon. Although several hypotheses are suggested by the cases, these hypotheses require confirmation through more robust testing procedures before they can be fully utilized to shape policy and practice. In addition to identifying and investigating additional cases of successful complex engineering efforts by VNSAs, it will be necessary to explore multiple instances of failed attempts to engage in complex engineering. This would enable the use of several qualitative and quantitative methods, such as case-control sampling and Qualitative Comparative Analysis,[6] to determine the extent to which any of the hypothesized factors are necessary, sufficient or merely strongly correlated with particular outcomes and indicators.

With respect to how this study can help to inform counterterrorist and law enforcement policy and practice, if the above hypotheses are indeed confirmed by further investigation, many of them can be directly employed as observable indicators to show when a VNSA has the intent to engage in, or is already engaging in, complex engineering efforts. This would be useful for intelligence analysis at the operational level. For example, among the potential indicators that might prove most useful in detecting and interdicting VNSA complex engineering efforts are: (1) Changes in a VNSA's strategic or tactical environment for which no simple operational adaptation will compensate and where there are no readily available suppliers of the necessary technology; or (2) Attempts by a VNSA to recruit, hire, coerce or otherwise acquire technical expertise.

The factors that point to an increased (or decreased) likelihood of a VNSA engaging in, and especially succeeding in, complex engineering efforts can

[6] For example, see Stolley, Paul and James Schlesselman, *Case-control studies: Design, Conduct, Analysis* (Oxford: Oxford University Press, 1982) and Rihoux, Benoît, and Charles Ragin (eds.), *Configurational Comparative Methods: Qualitative Comparative Analysis (QCA) and Related Techniques* (Thousand Oaks, CA: Sage Publications, Inc., 2009).

http://scholarcommons.usf.edu/jss/vol9/iss1/10
DOI: http://dx.doi.org/10.5038/1944-0472.9.1.1511

also inform strategic threat assessments, both of particular VNSAs and of classes of VNSAs such as transnational criminal organizations. Therefore, further research might confirm that the VNSAs that are most likely to pursue and succeed in complex engineering efforts are those which: (1) have a penchant for taking risks; (2) are willing and able to devote substantial resources to the effort for an extended period of time; (3) can conduct R&D through a specialized organ in a location of relative security; (4) tend to persevere in the face of setbacks; and (5) either already have, or can relatively easily acquire, the necessary expertise.

Overall, the current study has enriched our understanding of how and why VNSAs might engage in complex engineering efforts. It has shown that such endeavors will undoubtedly face a number of obstacles and requirements and thus hardly constitute *faits accompli*. Nonetheless, we must not underestimate the ability of VNSAs to accomplish remarkable feats of engineering in pursuit of their tactical and strategic goals. When organizational conditions are right, almost any technical task, even the most complex, become feasible for VNSAs.

Produced by The Berkeley Electronic Press, 2016