High Leverage Interventions: Three Cases of Defensive Action and Their Lessons for OR/MS Today

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This paper has two aims. First, to present cases in which scientists developed a defensive system for their homeland: Blackett and the air defense of Britain in WWII, Forrester and the SAGE system for North America in the Cold War, and Archimedes’ work defending Syracuse during the Second Punic War. In each case the historical context and the individual’s other achievements are outlined, and a description of the contribution’s relationship to OR/MS is given.

The second aim is to consider some of the features the cases share and examine them in terms of contemporary OR/MS methodology. Particular reference is made to a recent analysis of the field’s strengths and weaknesses. This allows both a critical appraisal of the field and a set of potential responses for strengthening it. Although a mixed set of lessons arise, the overall conclusion is that the cases are examples to build on and that OR/MS retains the ability to do high stakes work.

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1. Introduction

This paper has two aims. First, to present three cases in which scientists successfully developed a system to defend their homeland against attack. Second, to challenge readers to view the general OR/MS methodology today through the lens of those cases. The cases are of interest in themselves, but they benefit further from being considered together. Moreover, considering some of the features they share provides a critical comparison with contemporary OR/MS methodology and offers potential responses for strengthening the field.

The cases involve one of the founders (Blackett), an individual whose defense work had strong affinities with OR/MS (Forrester) and a scholar widely seen as a “precursor” of the field (Archimedes). Key elements of OR/MS can be seen in the three cases.

The nature of those key elements depends on the understanding of OR used. A 1983 UK defence operational research establishment booklet sees “The origins of Operational Analysis” in Alexander the Great’s post-battle discussions (Rowland 2006, p. 1). Alexander’s systematically questioning the effectiveness of past operations to improve future performance fits with the spirit of OR/MS. However, some additional scientific features are certainly needed to be comfortable using that particular label. Gass and Assad (2006), summarizing views widely expressed in the literature, propose two key elements: modeling and holism.

Modeling means generating abstract theories about an operation being studied and then using those theories to experiment with alternatives. Early accounts of OR/MS attach great importance to “imaginary models” (Goodeve 1948, p. 379), mathematical analysis and analytical methods (Morse and Kimball 1951, pp. 6–7 and p. 9), and mathematical models (Churchman et al. 1957, pp. 13–14 and Chapter 7). However, this element must be interpreted broadly. Gass and Assad (2006) acknowledge that it was not always present in early OR; statistical analysis and/or experimental field trials frequently substitute (see also Morse and Kimball 1951, pp. 7–10a).1 “Holism”—“consideration of a problem in terms of its relationship to an entire operation”—is seen as a distinguishing feature of OR/MS by Trefethen (1954, p. 53). A similar idea is advanced by Waddington (1948) and Morse and Kimball (1951). It is therefore unsurprising that OR/MS is seen as equivalent to “systems engineering” (Morse and Kimball, p. 10b) and “systems analysis” (Churchman et al. 1957, p. 7; Miser 1963, p. 671). In the three cases the key elements of modeling/data analysis and holism are used as tools for detecting work of an OR/MS nature.

The paper is structured as follows. In the next three sections the cases are described in turn. Some background is given, outlining the individual’s other achievements and the historical context of their defense-related work. This is followed by a description of that defense contribution and then its relationship to OR/MS. The paper’s final section
contains the comparison of some notable features of these cases with contemporary methodological thinking and ideas for potential responses.

2. Patrick Blackett

The first case concerns Patrick Blackett. One of the key individuals who developed the practice and theory of OR, his work related to the air defense of the United Kingdom during the Second World War.

2.1. Background

P.M.S. Blackett (1897–1974) was one of a new technocratic breed of British Navy officers and saw action during WWI (Hore 2002). He became a highly talented physicist, winning the 1948 Nobel Prize (Kirby 2003a). His defense system work occurred during the air conflict between Britain and Nazi Germany. To appreciate his contribution it is worth reprising attitudes toward aerial warfare in the mid-1930s (Kirby and Capey 1997). First, the immense casualties of WWI had led to a widespread wish to avoid large ground engagements. Second, the idea that this could be achieved using the destructive power of aerial bombing. Third, the general belief that aerial attacks would be irresistible; “the bomber will always get through” (British Prime Minister Stanley Baldwin, 1932).

The low quality of aircraft detection was at the heart of this belief. In the mid-1930s detection methods were acoustic and visual: parabolic devices sought the noise of approaching aircraft, while visual detection was attempted by ground-based observers using binoculars, or by Royal Air Force (RAF) crew flying fatigue-inducing patrols. Air exercises conducted in 1934 confirmed the inadequacy of the system—prompting Air Ministry civil servant A. P. Rowe to examine all 53 ministry reports on air defense and conclude that they lacked any useful ideas (Rowe 1948, Cunningham et al. 1984). However, his despairing conclusion resulted in the formation of the Committee for the Scientific Survey of Air Defence (CSSAD) in 1935.

2.2. Blackett and the Air Defense of Britain

Blackett’s various roles during WWII were central to the establishment of OR/MS (Kirby and Capey 1998, Haley 2002). In August 1940 his group “Blackett’s Circus” studied the use of radar to direct Army antiaircraft gunfire; in March 1941 he led the OR group at RAF Coastal Command; and in January 1942 he became “Director of Naval Operational Research.” However, our focus is on his role in the air defense story. It was as a member of CSSAD from 1935 onward that Blackett contributed to the consistent championing and enabling of the innovations that transformed Britain’s air defense.

Prompted by Robert Watson-Watt, CSSAD recommended radar as the basis of a new air defense system and funded experiments into its use. From May 1935 in Orfordness, Surrey and from spring 1936 at nearby Bawdsey Manor, staff worked on detection: extracting altitude, bearing, and range information from radar signals. In the summer of 1936 CSSAD authorized B. G. Dickens and a group of RAF officers to begin working at Biggin Hill Airfield, Kent on interception: integrating radar and ground-based observations to direct fighter pilots to attack enemy aircraft. Similar work was also conducted at Bawdsey. Civilian scientists there included G. A. Roberts, who studied the operational efficiency of the whole communications system, and E. C. Williams, who examined variations in performance of staff in early warning stations and ways of improving operator technique. Members of the CSSAD also directly consulted with RAF officers on the operational requirements of an early warning system (Air Ministry 1963).

CSSAD recognized that both the technological and operational aspects of radar required development if its potential was to be harnessed. Studies were commissioned in both areas. Moreover, the CSSAD-sponsored work became the pattern for subsequent “operational research” studies—in 1938 producing the name for the new discipline (Kirby 2003b).

These initiatives succeeded. Radar technology improved: the “chain home” network of early warning radar stations constructed around the coast could detect aircraft 160 km out, and different radar equipment detected low-altitude aircraft. The contribution of “OR” became particularly clear in 1939, during the last pre-war exercise. The improvements to the whole system were so apparent that the Commander-in-Chief of RAF Fighter Command, Air Chief Marshal Dowding, asked for the permanent transfer of some of the Bawdsey scientists (Rowe 1948). In June 1941 they became the “Operational Research Section, Fighter Command,” a testament to the effectiveness of having civilians work with military staff to address operational problems using a scientific approach.

Fighter response was only one element of air defense. The Army’s Anti-Aircraft Command faced the problem of how to use radar to aim their guns. In August 1940 a group formed around Blackett, subsequently becoming the “Army Operational Research Group.” “Blackett’s Circus,” as it was known, used a multidisciplinary, scientific approach (McCloskey 1987a). Its research was distinctively operational: radar equipment at gun sites did not perform as under test conditions. The group researched the actual operation of the equipment and improved performance. The work here and in subsequent organizations is described in two papers by Blackett, which are amongst the earliest OR/MS publications.

In the summer of 1940, when Nazi Germany prepared to invade Britain by sending its bombers, radar technology was in place and operating effectively—a result of the activities that flourished under the aegis of Blackett and his CSSAD colleagues. However, OR/MS had made one further contribution. Information from radar and observers was integrated in the “filter and operations room” at Fighter
Command. Here the positions of friendly and hostile aircraft were plotted on large maps. RAF controllers could ring Observer Corps sites to check sightings and could contact fighter squadrons and continuously monitor and adjust their interceptions (Price 2004). This development followed directly from the work on control room procedures by Williams and others.

In consequence, early in WWII the air defense of the United Kingdom was achieved by a highly sophisticated system of tightly integrated elements (see Figure 1). Radar reports of attacking aircraft arrived by telephone at Fighter Command for plotting. Sighting was supplemented and/or confirmed by visual data from Observer Corps posts. This information was coordinated in a plan position filter room. Information was exchanged with the relevant group and sector headquarters to direct the various responses. When attacking aircraft were far away, fighters were directed to intercept, their courses monitored by direction-finding radar stations. When attackers were closer, information was sent to direct anti-aircraft guns. Even closer, barrage balloons were launched, causing bombers to fly higher, reducing bomb-aiming accuracy.

In the summer of 1940, the United Kingdom had “the most efficient scheme of air defense in the world at the

**Figure 1.** Blackett and the air defense of Britain.
time” (PRO AIR 41/15 1944, pp. 564–565). Radar multiplied by 10 the effectiveness of the RAF, while OR/MS techniques increased that effectiveness further by a factor of two (Goodeve 1948, Kirby 2003b). The bomber offensive was beaten back.

2.3. “The Father of OR”

Consider now the extent of OR/MS in this work, using the key elements of modeling/data analysis and holism. Its holistic nature is seen in the successful bringing together of innovative radar technology, visual observation, clear information presentation, radio and telephone communication, and weapons technologies. Less apparent is the role of modeling. The analysis of data sets was a larger part of the CSSAD-sponsored work than abstract mathematical modeling. However, Blackett’s 1941 methodological reflections on the work of CSSAD show that such data analysis had mathematical foundations. For example, his “variational analysis” for calculating the marginal costs and benefits of different operational configurations was based on ideas of partial differentials. An example was the calculation of the best number of antiaircraft guns to be located together in a battery. However, explicit modeling did have its place, from the use of simple geometric models to calculate interception vectors for fighters, to Blackett’s equation for comparing the benefits of introducing new weapons versus improving the effectiveness of existing ones (Kirby 2003b).

While many people were involved in developing the UK air defense system, as a member of CSSAD and as head of a number of groups, Blackett played a key role. He spread OR/MS across all three British armed services and established its value to the war effort. His writings reflected on and advanced the new OR/MS methodology underlying this work. These activities are central to his status as “the father of operational research” (Zuckerman 1978, p. 266). OR/MS was employed by the British in a range of theatres (Air Ministry 1963) and in other countries, notably the United States (Morse 1986), becoming a significant reason for the Allied victory (McCloskey 1987b, c; Kirby 2000). Blackett was a central figure—and his achievements were grounded in his training in physics.

3. Jay Forrester

The second case concerns Jay Forrester, known to the OR/MS community for the system dynamics approach (Rand 2006, Lane 2006). His contribution to the air defense of North America has affinities with OR/MS.

3.1. Background

J. W. Forrester (born 1918) was raised on a cattle ranch in Nebraska. After a first degree in electrical engineering, he worked with MIT servo-mechanism pioneer Gordon Brown. They developed devices to stabilize radar platforms on ships and then ones that employed radar data to direct antiaircraft guns.

The context of Forrester’s defense system contribution was the Cold War. As WWII ended, the United States held the monopoly on atomic weapons—until August 1949, when the first Soviet bomb was tested. Attack by atomic-armed Soviet bombers seemed possible. This led to an American equivalent of CSSAD, the US Air Force’s Air Defense System Engineering Committee, or ADSEC (Jacobs 1986). Committee chair George Valley and his colleagues were responsible for studying the nation’s air defense. Exercises in June 1950 showed that the existing system offered little protection to attack, emphasizing the importance of ADSEC’s task (Buderì 1996).

3.2. Forrester and the Air Defense of North America

In 1944 Forrester was leading MIT’s Aircraft Stability and Control Analyzer (ASCA) project. The aim was to develop a servo-mechanical aircraft flight simulator in order to experiment with new aircraft designs. Forrester came to believe that digital technology was required, and in 1946 “Project Whirlwind” was founded to develop a high-speed digital computer to generate real time simulations (Redmond and Smith 1980). In 1947 Forrester became the director of MIT’s Digital Computing Laboratory, and the “Whirlwind I” computer occupied nearly 250 m². Yet by early 1950, delays, problems with memory reliability, and a tripling of the machine’s estimated development costs meant that continued funding by the Office of Naval Research seemed unlikely. Then ADSEC’s George Valley visited Forrester’s laboratory (See Figure 2).

ADSEC had developed a bold plan for a new radar-based air defense system using computer technology to process the signal data. Valley’s visit was part of a survey of computer projects. He decided that Whirlwind I could be the platform for the new system. Having already explored the contribution that computing could make to military information systems (Forrester et al. 1948), Forrester readily agreed. USAF funding started in March 1950.

ADSEC’s October 1950 report recommended what came to be called SAGE, for semi-automatic ground environment (Jacobs 1986). SAGE would defend the airspace over Canada and the United States. It was to be a network of radar stations and long-distance communication systems based on telephone lines. Target tracking information would be relayed to digital computers managing the data in real time and automatically triangulating signals to calculate the position and velocity of targets. This would then allow operators to deploy fighter aircraft and surface-to-air missiles in response to perceived threats. At its heart would be a development of the Whirlwind I computer (Astrahan and Jacobs 1983).

In July 1951 what became MIT’s Lincoln Laboratory was founded, with the aim of generating the technologies required for air defense. The Whirlwind researchers joined Division 6, Digital Computers. Led by Forrester, they began to develop Whirlwind II, the prototype for
Figure 2. Forrester and the air defense of North America.

Notes. Top left: magnetic core memory. Top right: Whirlwind I test control in 1950 with Forrester (standing centre left). Bottom: the various elements of US national air defense system. Pictures used with the permission of the MITRE Corporation. Copyright © the MITRE Corporation. All rights reserved.

the computer needed in SAGE. The computer was used to explore designs for military information systems. This started in 1951 with “Project Charles” and developed into the 1953 “Cape Cod System” experiments, which used data relayed from radar stations on Cape Cod to show that Whirlwind could be used to analyze digitized radar data supplied by telephone line to track approaching bombers and to direct interceptor aircraft (Forrester 2001).

While these experiments were a success, Whirlwind II was far from deployment. The need to increase the speed of the random access memory spurred Forrester to develop coincident-current magnetic core memory (Forrester 1951). Installed in 1953, access times dropped as core memory “doubled the operating speed [and] quadrupled the input data rate” (Jacobs 1983, p. 325). Such innovations produced the machine at the heart of SAGE: the 275-ton AN/FSQ-7
(Army-Navy fixed special equipment), essentially the production version of Whirlwind II and the first computer built in volume (Astrahan and Jacobs 1983).

Inevitably, SAGE involved the tackling of numerous different problems. Many individuals helped develop the radar elements. C. Robert Wieser was responsible for SAGE’s real-time software (then the world’s largest computer program). Enormous amounts of information were central to the SAGE concept (Enticknap and Schuster 1958), and the problem of transmitting digital information over telephone lines was solved under the direction of Jack Harrington using technology that presaged today’s modem (Harrington 1983).

In July 1958 the first direction centre became operational, and the whole SAGE system was completed in 1963. Attacking aircraft were identified by radar. This information was relayed to 24 direction centers, each operating two AN/FSQ-7 computers in duplex mode. The information was processed and various responses coordinated. When the attacking aircraft were far away, fighters could be directed to intercept. When attackers were closer, location information was used to direct antiaircraft missiles. In the direction centers data were presented to operators as real-time displays on cathode ray tubes, with "light pen" pointing devices used by operators to designate specific targets on their screens and so get information on height and bearing (Everett et al. 1983). The display method and the pointing devices were key innovations in interactive computing (Palfreyman and Swade 1991).

The last SAGE computer centre was decommissioned in 1984. Although never tested by a mass attack of Soviet bombers, the system is judged to have been very reliable (see, for example, Jenkins and Landis 2004), a source of evident pride to Forrester (1992).

### 3.3. Affinities with OR/MS

As CSSAD was similar to ADSEC, so the fruits of those committees bear comparison. Although technologically more advanced, SAGE was quite like the UK air defense system. It faced many of the same problems and addressed them using an approach that included key elements of OR/MS. Holism is evident in the effective integration of innovative computing technology, human-computer interface methods, radio and telephone line communication, and weapons technologies.

Elements of modeling/data analysis are seen in various ways. One specific example of mathematical work is the development of the United Kingdom’s simple geometric modeling for fighters: “The next evolutionary step, which took place early in the era of Project Charles, was to program Whirlwind to compute collision-course vectoring instructions for an interceptor aircraft automatically” (Wieser 1983, p. 365). A second example is the Project Charles and Cape Cod System explorations that used Whirlwind as a defense information system. These went beyond technical proof of concept and solving system integration problems: they were experimental field trials in the broadest sense. “The Cape Cod System was...a model of the SAGE system, scaled down in size but realistically embodying all the SAGE air-defense functions” (Wieser 1983, p. 366). As such "[it] was intended to demonstrate the operations that were to be executed for field use" (Astrahan and Jacobs 1983, p. 342). The 1950 Whirlwind could only display the solution to a simple mechanics problem on a cathode ray screen; the Cape Cod System work—activities comparable to the CSSAD-initiated OR work at Bawdsey on improving radar operator technique—led to the sophisticated real-time displays and “light pen” pointing devices. A final example is the project management modeling used to propose a detailed 15-year plan for developing military and other information systems based on digital computing (Forrester et al. 1948). This document includes measures of project scope, proposed activities, and key milestones. Fine-grained calculations for resource usage produce graphs over time of spending and staff employed, while a set of cost-vs.-duration curves present an analysis of project acceleration options. This plan, formulated before ADSEC ever met, indicates the forward thinking of Forrester and his group and provides a context for SAGE’s development.

In 1956 Forrester moved to MIT’s new Sloan School of Management (Forrester 1992). He argued that servomechanistic concepts were relevant to management (Forrester 1956, 1958); soon “system dynamics” was born (Forrester 1961).

Returning to Forrester’s defense system work, naturally he was one of many people involved. In particular, Valley is known as “the father of SAGE.” Nevertheless, Forrester’s achievements were considerable. He “guided the planning and design of the SAGE system” (Everett 1983, p. 321), this broad contribution having affinities with OR. As he reflected on joining Sloan, “moving to a management school was not a break from a purely technical background. I was already in management. We had been running a vast operation...from basic research to military operational planning” (Forrester 1992, p. 343). Forrester was a central figure in SAGE—and his achievements were grounded in his knowledge of servo-mechanism theory and computing.

### 4. Archimedes

The final case concerns the system Archimedes developed to defend his home city of Syracuse.

#### 4.1. Background

Archimedes (287-212 BCE) ranks amongst the greatest mathematicians and physicists (Drachmann 1968). He studied natural phenomena to understand their underlying principles and then experimented to test his theories—a key shift into a scientific way of understanding the world. He made major contributions to astronomy and geometry. In mechanics he formulated the principle of the lever and is
credited with inventing compound pulleys. He also discovered that a floating body displaces a mass of liquid equal to its own mass and studied the stability of floating bodies.

The focus here is his defensive preparation for the siege of Syracuse. This work is often cited as an example of scientists and military personnel cooperating (Flood 1962, Air Ministry 1963), and others refer to Archimedes as a “precursor” or “Vorläufer” of OR/MS (respectively, Trefethen 1954, Brusberg 1965). Larnder, who worked in Fighter Command’s OR section, refers to Archimedes as someone who “studied warlike operations and carried out analysis that might well qualify as ‘operational research’” (Larnder 1984, p. 466).

The context was the Second Punic War (218-202 BCE), in which Carthage and Rome contested control of the Mediterranean. While allied with Rome, Syracuse’s King Hieron II asked Archimedes to improve the city’s defenses. When Hieron died in 215, the new rulers sided with Carthage—and a Roman attack became a certainty.

To develop a critical examination of Archimedes’ contribution, the primary source is The Histories (Polybius 1923). Polybius (c. 200—after 118 BCE) had a good understanding of military matters and might have interviewed eye witnesses to the siege (Burrow 2007). Other sources are Livy (1965) and Plutarch (1912). In addition, work on Greek engineering (Landels 1978), military operations (Connolly 1998), and the machinery and tactics of sieges (Kern 1999) have been drawn on to assemble the account below.

4.2. Archimedes and the Defense of Syracuse

Archimedes’ response to Hieron’s request was a systematic examination of the city’s defense requirements, followed by a program of action. This included raising, strengthening, and adding to the city’s walls and designing both specific “engines” and an appropriate system for operating them effectively: “Archimedes now made... extensive preparations, both within the city and also to guard against an attack from the sea” (Polybius 8.3.5).

Knowing, from lookouts, the position of an attacker, there might be a variety of responses. At a distance, large rocks or spears could be thrown by catapult artillery. Closer to, smaller arrows could be employed. Very close, objects could be dropped directly onto an enemy. Syracuse had all these responses available—and more. The point upon which the three historians agree is the layered nature of the system. For example, “Archimedes... had prepared engines constructed to carry to any distance” (Polybius 8.5.2).

In 213 BCE the Roman 22nd and 23rd legions arrived with 60 ships. Appius Pulcher led the army while Consul Marcus Marcellus commanded the fleet. Plutarch tells us “But the apparatus was, in most opportune time, ready at hand for the Syracusans, and with it also the engineer himself” (Plutarch Marcellus, 14.9). The Romans planned to take Syracuse in five days; “but in this they did not reckon with the ability of Archimedes, or foresee that in some cases the genius of one man accomplishes much more than any number of hands” (Polybius 8.3.3).

A joint land and sea attack followed. The defenders watched Marcellus’ ships approach and aimed the appropriate weapon. Polybius describes how Archimedes “so damaged the assailants at long range...with his more powerful [stone-throwers] and heavier missiles as to throw them into much difficulty and distress” (Polybius 8.5.2, with correction). Such catapults utilized both lever-based and pulley-based mechanisms. Then, “as soon as these engines shot too high he continued using smaller and smaller ones as the range became shorter, and...put a complete stop to their advance” (Polybius 8.5.3).

Later, attempting a night assault, Marcellus encountered the close-range defenses as archers and small “scorpion” catapults shot through slits cut low in the sea wall. Nevertheless, close engagement was needed to bring up “sambucae,” ship-mounted walkways across which Roman marines could storm the walls. These encountered the next layer of Archimedes’ defense system: large cranes that swung out over the walls and dropped objects weighing up to 250 kg onto the vessels. More levers and pulleys were in use. A final type of “engine” used is known as Archimedes’ “shiplifter” (James and Thorpe 1995), or his “iron hand,” a crane:

...with which the man who piloted the beam would clutch at the ship, and when he had got hold of her by the prow, would press down the opposite end of the machine...Then when he had thus by lifting up the ship’s prow made her stand upright on her stern, he...by means of a rope and pulley let the chain and hand suddenly drop from it...[S]ome of the vessels fell on their sides, some entirely capsized, while the greater number...went under water and filled. (Polybius 8.6.2-4)

Pulcher’s land assault had faced a similarly layered defense and suffered a similar fate. Plutarch comments, “the rest of the Syracusans were but the body of Archimedes’ designs, one soul moving and governing all” (Plutarch Marcellus, 17.2). The Romans abandoned direct assault. After a prolonged siege, drunk and inattentive guards allowed the Romans to storm the city. Archimedes was killed.

4.3. Precursor to OR/MS

Archimedes’ contributions lay in three areas (see Figure 3). First, the devices operating at the city walls. The cranes and “iron hands” derived from existing technology, but the latter was clearly tailored to the specific needs of the situation, surely drawing inspiration from Archimedes’ work on the stability of floating bodies (Rorres and Harris 2001). Second, the deployment of catapults. This technology was well developed; Archimedes’ contribution was the design of the layered artillery defense. The Romans would have expected to face projectile weapons; not being able to find gaps in their coverage is what surprised them. Last, his development of the city’s fortifications: the walls, ditches, and
Figure 3. Archimedes and the defense of Syracuse.

Notes. Top left: a large torsion catapult, showing the diameter of the spring. Top right: an “iron hand” capsizing a quinquireme; note the slits at the base of the wall. Bottom: reconstruction of the Euryalos fort, whose artillery tower (a), protective barriers (b), and outer ditch (c) defended the city’s gate (d).

outworks. Most striking is the Euryalos fort that defended the city’s gate, but all the 27 km of walls made Syracuse one of “two sites...whose defensive systems display a complexity almost unrivalled in the Hellenistic world” (Winter 1967, p. 363).

Elements of OR/MS can be discerned here. Modeling/data analysis was certainly present. Consider the cranes and iron hands, and recall that Archimedes formulated the mathematical principles underlying levers and pulleys. Another usage concerned catapults. By the end of the third century BCE, catapult technology was widely used (Campbell and Delf 2003, Rihll 2007), so Archimedes strengthened the city walls and built protective barriers for the city gate to resist catapult fire. As reflected in the technical manuals of the period, analysis of field experiments had led to standard designs (Marsden 1969). Constructing a standard machine required use of a formula for the diameter of the torsion spring, \( D \) (in Athenian dactyls). In the case of a stone-thrower

\[
D = 1.1 \times \sqrt{100 \times M},
\]

where \( M = \text{Weight (in Athenian minae)} \).

The size of every component followed directly: breadth of the spring frame \((6\frac{1}{2}D)\), thickness of the stanchions \((\frac{5}{8}D)\), etc. Although these standard catapults started with the same range, they could subsequently be used to achieve different distances of shot. This is how the layered defense might have been achieved: Archimedes could design his defenses at a systemic level, imagining where he might place catapults and what range was required, and then use the formula to specify the dimensions of each artillery piece.

The consequences of such calculations can still be seen in the stones of the Euryalos fort. For example, the protective barriers meant that any catapults directed against the
gate needed to move within range of the catapults on the artillery tower. Similarly, the positioning of the outermost ditch meant that assaulting catapults would be \( \sim 180 \) m from the tower and “outside the effective…range of the most powerful [catapult], the type which could throw a 50-pound stone” (Lawrence 1946, p. 105). In contrast, the tower’s elevation meant that attackers at the outer ditch could be struck by Syracusan artillery. In this sense, modeling was central to the work in Syracuse, playing a key role in the grand design.

The holistic nature of this work is clear. From strengthening walls to positioning catapults and cranes, how these elements would work together had been thought through with great care. Hence, “It is [Archimedes’] comprehensive, systematic approach to the art of warfare that is unique” (Simms 1995, p. 68).

Archimedes was involved in the design of this system in a central way—and his achievements were grounded in his knowledge of geometry, physics, and mechanics.

5. Methodological Discussion

The three cases benefit from being seen together because their parallels become apparent. This section goes further by discussing whether they have general methodological lessons for OR/MS today.

Because the cases are success stories, the following questions arise. In terms of OR/MS methodology, what notable features do they share? How do those features compare with contemporary OR/MS? These questions are addressed as follows. First, some of the features that contributed to the success of the cases, and that are common to the three, are identified. Second, to make a comparison with modern OR/MS, a recent analysis of the “OR/MS ecosystem” is used (Sodhi and Tang 2008). This analysis is chosen because it emerged from discussions at the 2006 INFORMS meeting. Finally, using that comparison, an additional question is asked: if current OR/MS methodology is found wanting, then what response is needed?

5.1. Personalities

Four features relate to the personalities of those involved in the cases (see Table 1).

First, the individuals had training and achievements in various disciplines not obviously related to the tasks. All brought an element of interdisciplinarity; Blackett’s emphasis on interdisciplinary teams became a characteristic of OR/MS (see Churchman et al. 1957, Chapter 22).

Sodhi and Tang’s analysis finds modern OR/MS continuing to draw on multiple disciplines, viewing this as a major strength. This chimes with an earlier recommendation that “interdisciplinarity be taken seriously” (Ackoff 1979, p. 101). The appropriate response, surely, is to take it as a feature to be valued and sustained.

A second notable feature is that all were interested in putting scientific ideas into practice to develop real improvements. In contrast, Sodhi and Tang see the disengagement of research and practice as a key weakness of OR/MS today. They attribute this to an “imbalance” in journal publications (practical papers declining in relative number) and an orientation towards tools rather than problems. Sodhi and Tang recommend connecting more strongly with end-users, suggesting more practice-driven research and new publications tailored to appeal to end-users. But how to persuade young colleagues to allocate time implementing—rather than constructing—their ideas? Clearly the incentive structure today is significantly different from that in the three cases.

A third feature is the organizational level of the work done. It is the holistic perspective that is most apparent: the concern with methods of operating whole systems of interacting components. Sodhi and Tang report that modern

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<td>Training and achievements in other disciplines</td>
<td>✓ OR/MS continues to draw on multiple disciplines</td>
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| Interest in putting ideas into practice | ? Disengagement of research and practice; retreat from practical applications | ➔ Strengthen end-user links:  
—More practice-driven research  
—More tailored publications |
| Concerned with methods of operating whole systems | ? Tends to solve narrow parts of complex problems; less impact at strategic level | ➔ Rebalance strategic/operational level focus:  
—Use success stories as levers to get access  
—Deliver with “strategic approaches” |
| Access to, and credibility with, high-level decision makers | ? Low profile and unclear identity of OR/MS | ➔ Incentivize OR/MS workers to be familiar with “sharp end” practicalities  
➔ Reflect this in branding |

Note. See text for detail and references.
OR/MS tends not to be involved in high level issues, the interest in tools and in solving “a narrow part of a complex problem” (p. 270) tending to locate work at the operational level. This chimes with previous concerns about the field’s “lack of impact on strategic issues” (Zahedi 1984, p. 58). Sodhi and Tang acknowledge the need to “rebalance the focus between strategic and operational levels” (p. 273). They recommend using success stories as levers to create management interest further up organizations. Whether any specifically “strategic” approaches are also needed to deliver effective work is considered in §5.2 below.

A final feature is that the individuals had access to people at high levels and had credibility with them. Archimedes demonstrated his pulley and lever ideas to King Hieron by moving a beached ship back into the water (Simms 1995). The king’s response was that “from that day forth Archimedes was to be believed in everything that he may say” (Heath 2002, p. xix). A plainer statement of client confidence is hard to find. In sharp contrast, Sodhi and Tang report as an important weakness the unclear identity of OR/MS, relating this to poor levels of access at high levels. This clearly overlaps with the previous feature: the respect commanded by the three individuals can be contrasted with the low profile of OR/MS amongst top managers identified by Bell and Anderson (2002). For Blackett and Forrester, military experience might have been a factor. Blackett served at the Battle of the Falkland Islands and at Jutland (Lovell 1988). Forrester’s decision in 1943 to stay with the USS Lexington to repair a stabilizing device meant that he was present when the carrier participated in the retaking of the Marshall Islands and was torpedoed. Exposure to the sharp end of the task cannot have harmed their credibility in the eyes of those they sought to influence—and Morse and Kimball (1951) stress the need for familiarity with actual practice and first-hand experience. What is today’s equivalent? For individuals, experience in organizations via previous jobs, placements, and consulting assignments. For the whole profession, incentives that acknowledge the value of such experience. Responding to the concerns about the field’s identity, these changes also need to be reflected in the clear branding of OR/MS as a discipline with an understanding of the “sharp” end. This would increase the chances of obtaining high-level access and offering recommendations with credibility.

5.2. Context

Three notable features emerge when considering the contexts of the cases (see Table 2).

First, modeling/data analysis tools were relevant and effective. Sodhi and Tang see the ability to create new theories offering both generality and elegance as one of the field’s greatest strengths. Considering the advances made since the experiences of the three cases, it is clear that the use and continued development of modeling is a hallmark of OR/MS and is central to its success.

Second, these were predominantly “technocratic” problems. The usefulness of modeling tools is one aspect of this, but there are others: the problems were clear, there was consensus about the aims of the work, and implementation was via hierarchical chains of command. Such problems exist today, and OR/MS retains its ability to tackle them. However, in this regard the cases offer slightly too narrow a lesson; other types of problems exist, and OR/MS can contribute to these also. With more “sociotechnical” problems the individuals concerned and how they work together are as much elements of the situation as any analytical problem (Pasmore and Sherwood 1978). There might be no consensus about the problem definition; aims might be hard to agree on, and implementing change might require support from a range of stakeholders. The earliest OR/MS publications certainly emphasized the need to address the human relations aspect of problems—hence the discussion above on credibility. However, as the limitations of a purely analytical approach were recognized (Hoos 1972, Lee 1973), critiques of OR/MS appeared in both the United States (Caywood 1970, Zahedi 1984) and Britain (Rosenhead and Thunhurst 1982, Checkland 1972, Jackson 1982, Eden 1982, Rosenhead 1989a). Today, Sodhi and Tang report that OR/MS might be neglected by top managers exactly because it is primarily about “problem solving” not “problem defining.”

They also see the relative absence of discussions about how to generate actual

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Table 2. Notable features relating to the context of the three cases, comparisons with OR/MS today, and potential responses.

<table>
<thead>
<tr>
<th>Feature relating to context</th>
<th>Comparison with contemporary OR/MS</th>
<th>Potential response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modeling/data analysis beneficial</td>
<td>✓ Power and generalizability of theory building is a key strength</td>
<td>Retain as hallmark of field and continue use and development</td>
</tr>
<tr>
<td>Predominantly technocratic problem</td>
<td>✓ OR/MS very effective here</td>
<td>Continue such work but also…</td>
</tr>
<tr>
<td>High stakes, conflict situation</td>
<td>✓ Problems exist in these domains but in other domains too.</td>
<td>Retain confidence in OR/MS ability to solve important problems</td>
</tr>
</tbody>
</table>

Note. See text for detail and references.
change in organizations as a weakness of OR/MS, caused by its “tool-orientation.” In fact, recent decades have seen the development of modeling tools and approaches appropriate for more sociotechnical situations (Ackoff 1981; Rosenhead 1989b, 1996). Effective work in organizations has resulted (Ormerod 1996, Eden and Ackermann 2004, Mingers and Rosenhead 2004). Note that “technocratic” and “sociotechnical” are not a dichotomy; rather, two points on a spectrum. A sense of balance is key: “The technocratic view is faulty, not because it is incorrect, but because it is incomplete” (Tinker and Lowe 1984, p. 45). The opportunity here is for OR/MS to be used in exciting areas different from those in the three cases, ones in which human relations play an increasing role, and yet still applying the field’s hallmark of rigorous modeling. These sociotechnical approaches might also be useful for performing the systems level, or “strategic” work, mentioned in §5.1.

The final notable feature is that these were high stakes, direct conflict situations. Sadly, the defense and security applications community faces not dissimilar situations today. However, for most OR/MS people, lives are not in the balance. Does this mean that OR/MS cannot normally expect the scale of accomplishment seen in these three cases? That does not follow. War is not the only circumstance where there is value in getting things right. Although business is not war, competition between companies should expose inefficiencies and errors. Sodhi and Tang see the extra risk produced by the globalization of supply/service chains as one opportunity for OR/MS, and it is easy to add examples: from revenue management and optimized maintenance schedules by airlines to the inventory control underwritten by OR/MS algorithms in large supermarket chains, sound analysis continues to provide benefit to millions of people around the world. No one would describe these as low-stakes situations, and there are many more to which OR/MS can contribute boldly.

5.3. Closing Remarks

This discussion offers a mixed set of lessons: contemporary OR/MS strongly retains many of the success factors in the three cases—but not always all. Not surprisingly, debate about ways of improving the methodology of OR/MS is widespread. Important as such methodological considerations are, it is worth retaining confidence in the field’s ability to improve an extraordinarily wide range of situations. Additionally, it would be wrong to be so impressed by the achievements of Blackett, Forrester, and Archimedes that they are seen as past glories, never to be repeated. They are exemplars of what OR/MS is capable of, successes to be built upon boldly when looking for the next high-stakes problem.

Archimedes showed such boldness. Having moved the boat off the beach, Archimedes’ reply to King Hieron tells us what OR/MS is capable of today: “There is no limit. Just give me somewhere to stand, and I shall move the earth” (Drachmann 1958, p. 281). This is the most important methodological lesson of these three cases: our field is still capable of high leverage interventions.

Acknowledgments

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Endnotes

1. The two aspects are seen in Lanchester’s (1916) equations for forces in combat and Edison’s analysis of statistical data relating to antisubmarine warfare when he was president of the Naval Consulting Board (Scott 1920, Whitmore 1953).

2. “Scientists at the Operational Level” (1941) and “A Note on Certain Aspects of the Methodology of Operational Research” (1943); available in Blackett (1948, 1962, 1995).

3. The convention of citing ancient sources by book and chapter number of the original texts is used here. However, the specific translations are cited in the text and listed in the references.

4. On this point also, practice has diverged from the sound recommendations of Morse and Kimball (1951). See “The problem of finding the problem” (pp. 5–6).

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