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Beyond Simulation: Developing Integrated Cyber Range Solutions for Real-World Security Challenges

MBA Project
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1. SAHA İstanbul Yönetim Kurulu kararıyla, 2024-2025 eğitim döneminden itibaren SAHA AKADEMİ MBA katılımcılarına "Araştırma Projesi" hazırlama yükümlülüğü getirilmiştir. Bu uygulama; katılımcıların sektörel bilgi, stratejik düşünme ve akademik üretkenlik yetkinliklerini geliştirmeyi hedeflerken, savunma sanayii ekosistemine bilimsel katkıyı artırmayı amaçlamaktadır. Bu girişim, Türk savunma sanayii ekosisteminde bilimsel katkıyı artırmaya yönelik önemli bir adımdır.

2. SAHA İstanbul-SAHA AKADEMİ tarafından yayımlanan bu çalışma, ilgili yazar tarafından özgün biçimde hazırlanmış ve beyan edilmiştir. Çalışmada yer alan görüşler yazara ait olup, SAHA İstanbul'un kurumsal görüşünü yansıtmamaktadır. İçerikte sunulan bilgi, yorum ve sonuçların doğruluğu sorumlu yazara aittir. SAHA AKADEMİ; benzerlik oran tespitini yapmıştır.

3. Bu çalışma, [Emrecan Arda] tarafından hazırlanmıştır. Araştırma Projesi danışman tarafından değerlendirilmiş ve sunumu [25 Mayıs 2025] tarihinde yeterli görülerek kabul edilmiştir.

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BEYOND SIMULATION: DEVELOPING INTEGRATED CYBER RANGE SOLUTIONS FOR REAL-WORLD SECURITY CHALLENGES

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Executive Summary

This project proposal examines the strategic implementation of cyber ranges as a critical component of organizational cybersecurity preparedness. Cyber ranges are virtual environments that simulate real-world IT infrastructure and cyber threats. They represent a significant resource for academic institutes, government agencies and commercial businesses to enhance their security posture in an increasingly hostile digital landscape.

The objective of this research is to develop guidance for academic institutes, government agencies and commercial businesses to evaluate, implement, and optimize cyber range capabilities aligned with their specific objectives and risk profiles. This project will address the current gap between theoretical cyber range benefits and practical business applications.

The output of this project proposal will include: (1) a decision matrix for cyber range technology selection based on organizational needs; (2) an implementation roadmap addressing technical, financial, and operational considerations; and (3) strategies for integrating cyber range training into broader organizational resilience planning.

As cyber-attacks continue to evolve in sophistication and frequency, organizations that effectively leverage cyber ranges gain measurable advantages in incident response capabilities, regulatory compliance, and talent development - all translating to reduced breach costs and enhanced business continuity.

Introduction

1.1. Background and Context

In today's hyper connected business environment, cybersecurity has evolved from an IT concern to a critical business imperative. Organizations face an increasingly sophisticated threat landscape, with the global average cost of a data breach reaching $4.45 million in 2023, according to IBM's Cost of a Data Breach Report. Despite growing investments in cybersecurity technologies and personnel, many organizations remain vulnerable due to a fundamental gap in operational readiness which is the ability to effectively respond when attacks inevitably occur.

Cyber ranges have emerged as a powerful solution to this preparedness gap. Originally developed for military and intelligence applications, these virtual environments simulate real-world IT infrastructure and security scenarios, allowing organizations to train personnel, test defenses, and refine incident response protocols without risking production systems. While adoption has accelerated in government and critical infrastructure sectors, many commercial enterprises have yet to fully leverage cyber ranges as strategic assets for business resilience.

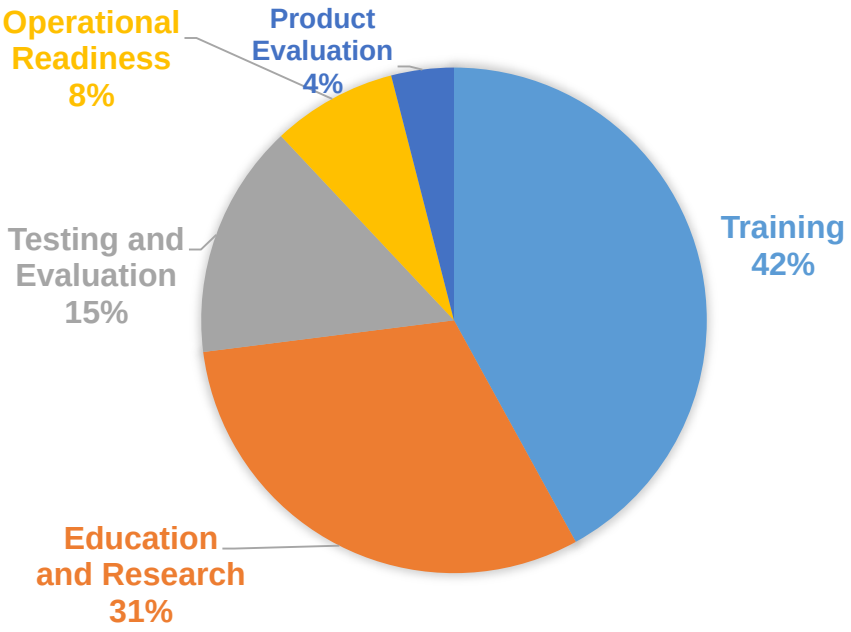

Figure 1. Cyber Range Use Case Distribution

Source: (Ukwandu, et al., 2020))

Figure 1 shows the use case distribution of cyber ranges. The percentages reflect the primary purposes for which cyber ranges are deployed across different sectors. Training (42%) represents the use of cyber ranges for cybersecurity professional development and skill enhancement. Education and Research (31%) covers academic applications including teaching and scientific investigation. Testing and Evaluation (15%) encompasses security validation and vulnerability assessment activities. Operational Readiness (8%) refers to exercises designed to prepare teams for actual cyber incidents. Product Evaluation (4%) involves using cyber ranges to test security products and solutions before deployment.

This distribution highlights the versatility of cyber ranges while showing their predominant use for training and educational purposes.

1.2. Problem Statement

Despite their proven effectiveness in enhancing cybersecurity capabilities, organizations face significant challenges in implementing and operationalizing cyber ranges. These challenges include:

a. Difficulty quantifying return on investment and articulating business value beyond technical security metrics
b. Uncertainty in selecting appropriate cyber range architectures and technologies aligned with specific organizational needs
c. Integration challenges with existing security programs, training initiatives, and governance structures
d. Limited frameworks for measuring effectiveness and maturity of cyber range implementations
e. Insufficient guidance on scaling cyber range capabilities as organizations evolve

This research addresses these challenges by developing a guideline for cyber range implementation that bridges technical capabilities with strategic objectives.

1.3. Research Objectives

This project aims to accomplish the following objectives:

a. Evaluate the current state of cyber range adoption across industries, identifying key success factors and common implementation barriers
b. Develop a decision framework for organizations to assess cyber range requirements based on their risk profile, regulatory environment, and security maturity
c. Create a practical implementation roadmap addressing technical architecture, governance, staffing, and operational considerations
d. Formulate strategies for integrating cyber range capabilities with broader business continuity and resilience planning

1.4. Scope of the Study

This research will focus primarily on government agencies and commercial businesses of mid-to-large enterprises across different sectors like financial services, healthcare, manufacturing, and technology. While technical aspects of cyber range implementation will be addressed, the primary emphasis will be on business strategy, organizational alignment, and value realization rather than specific technical configurations.

The study will examine both different cyber range solutions and implementations, considering implementation models and architectural approaches. Additionally, the research will explore emerging trends including AI-powered attack simulation, supply chain security scenarios, and integration with threat intelligence platforms.

By addressing these elements, this project will provide insights into how organizations can transform cyber ranges from specialized technical tools into strategic business assets that enhance organizational resilience in an increasingly volatile digital landscape.

2. Literature Review

2.1. Evolution of Cyber Range Concepts and Applications

The concept of cyber ranges has evolved significantly since its military origins in the early 2000s. Davis and Magrath (2013) provided one of the first comprehensive academic

examinations of cyber ranges, defining them as "interactive, simulated representations of an organization's local network, system, tools, and applications connected to a simulated Internet level environment" (Davis & Magrath, 2013). Their work established the foundational understanding that cyber ranges serve multiple purposes beyond basic training, including "technology evaluation, security validation, and mission rehearsal" (Davis & Magrath, 2013).

Subsequent research by Yamin, Balto , Shalaginov, & Katt, 2023 expanded this definition to incorporate the educational dimension, positioning cyber ranges as "pedagogical environments for cybersecurity education" that bridge theoretical knowledge and practical skills (Yamin, Balto , Shalaginov, & Katt, 2023). This educational perspective has been further developed by Ukwandu et al. (2020), who documented the growing integration of cyber ranges into academic curricula and professional certification programs to address the global cybersecurity skills shortage (Ukwandu, et al., 2020).

2.2. Business Value and Strategic Alignment

The business value of cyber ranges has been examined through different papers in the literature. Chouliaras, et al. (2021.) conducted a systematic review of cyber range implementations across industries, finding that organizations with mature cyber range programs demonstrated measurable improvements in incident response times and breach containment capabilities (Chouliaras, Kantzavelou, Maglaras, & Pantziou, 2021). However, their research also highlighted significant variation in how organizations measure and articulate this value to executive stakeholders.

The strategic alignment of cyber ranges with broader business objectives was explored by Vykopal, et al. (2017.) who proposed a framework for integrating cyber range exercises with enterprise risk management processes. Their work emphasized that cyber ranges provide greatest value when scenarios reflect an organization's specific threat landscape and business context rather than generic technical challenges (Vykopal, Ošlejšek, Čeleda, Vizváry, & Tovarňák, 2017).

Recent industry insights underscore that robust cybersecurity investments deliver tangible, quantifiable business value. For instance, IBM’s 2024 Cost of a Data Breach Report (IBM, 2024) indicates that the global average cost of a data breach has reached approximately 4.88 million per

incident, with sectors such as healthcare and finance incurring even greater losses — with incident costs sometimes exceeding 9 million. Organizations that implement proactive measures, including regular cyber range exercises and AI-enabled incident response tools, have recorded cost reductions of over 1 million per breach. In some cases, these advancements have been associated with an estimated annual preservation of up to 20 million in business value by preventing extended downtime, operational disruptions, and reputational damage. This quantifiable improvement not only bolsters the overall resilience of the organization but also enhances its ability to align cybersecurity investments with strategic business outcomes. These data-driven insights deliver a compelling case for integrating advanced cybersecurity measures into executive-level planning and risk management, thereby transforming cybersecurity from a technical expenditure into a strategic business investment.

2.3. Implementation Models and Architectural Approaches

Based on the literature, particularly Davis and Magrath (2013) and Ukwandu et al. (2020), cyber ranges can be implemented using four primary approaches, each with distinct characteristics, advantages, and limitations:

2.3.1. Simulation

Simulation-based cyber ranges use software models to represent real-world components and systems. These models interact according to predefined rules to mimic the behavior of actual networks, systems, and attacks. As Davis and Magrath (2013) note, "Simulations have high scalability and generally operate on either a single or a small number of servers. Therefore, they are easy to deploy and relatively cheap to install and maintain". Simulation approaches are particularly valuable for academic environments where cost constraints are significant and the primary focus is on teaching fundamental concepts rather than high-fidelity operational training.

2.3.2. Emulation

Emulation-based cyber ranges run actual software applications on dedicated hardware or virtual machines that are configured to replicate real-world environments. Davis and Magrath (2013) explain that "Emulation CRs support high fidelity testing. Since emulation uses real computers, operating systems and applications with limited resources, the experiments represent a realistic environment". This approach provides greater realism than simulation but typically requires

more resources. Government agencies often prefer emulation for its ability to accurately represent operational environments and support advanced training scenarios.

2.3.3. Virtualization

Virtualization-based cyber ranges leverage technologies like hypervisors and containers to create multiple virtual instances of operating systems and applications on shared physical infrastructure. This approach, which has gained significant traction in commercial environments, offers a balance between the scalability of simulation and the fidelity of emulation. As Ukwandu et al. (2020) observe, virtualization offered greatest scalability and cost efficiency while still providing sufficient realism for most training and testing scenarios. Commercial businesses typically favor virtualization for its operational efficiency and integration with existing IT infrastructure.

2.3.4. Hybrid

Hybrid approaches combine two or more of the above implementation methods to leverage their respective strengths. For example, a hybrid cyber range might use emulation for critical network components that require high fidelity while employing simulation for less critical elements where scale is more important than precise replication. According to Ukwandu et al. (2020), hybrid models provide the optimal balance between fidelity and operational flexibility for most enterprise use cases. This approach is increasingly common in sophisticated implementations across all sectors, though government agencies have been particularly active in developing hybrid cyber ranges to support complex training scenarios.

Figure 2 is a representation of cyber range implementation approaches by sector:

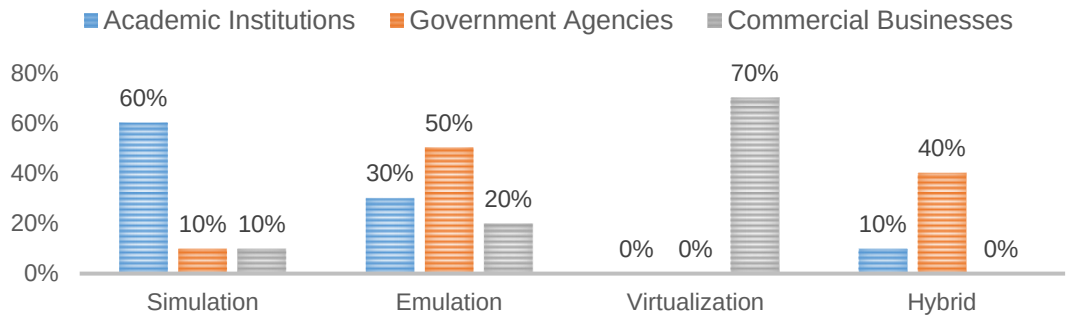

Figure 2. Cyber Range Implementation Approaches by Sector

Sources: (Davis & Magrath, 2013) and (Ukwandu, et al., 2020))

Each implementation approach has their own strengths. Figure 3 shows each approaches strengths on a scale of 1 to 10.

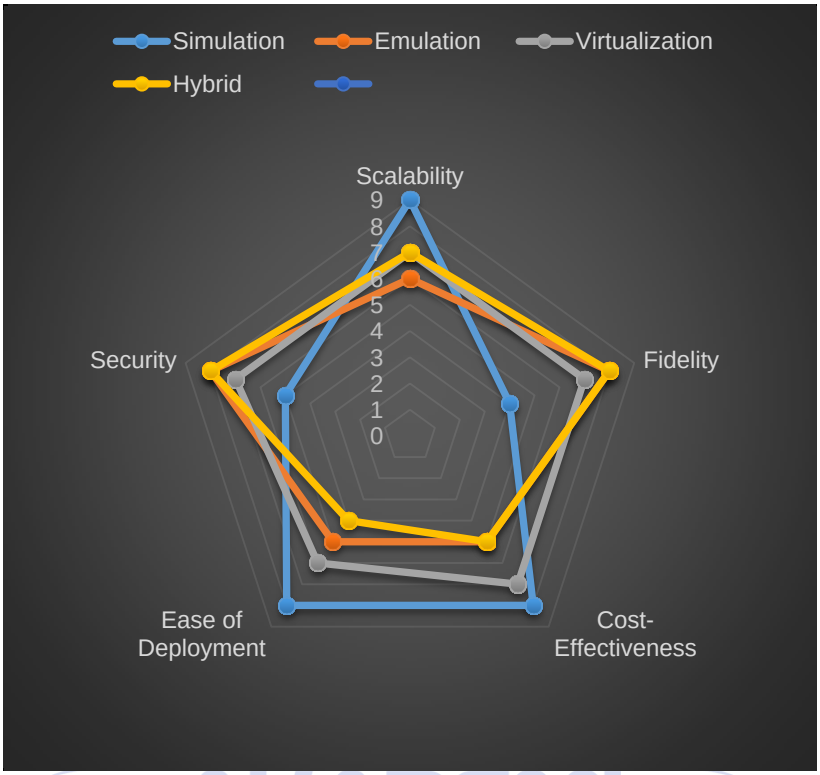

Figure 3. Cyber Range Feature Comparisons

Sources: (Davis & Magrath, 2013) and (Ukwandu, et al., 2020)

2.4. Challenges and Limitations

Several researchers have identified persistent challenges in cyber range implementation. Vykopal. et al. (2017.) Conducted a comprehensive analysis of cyber range deployments, finding that the most common barriers to effective utilization included difficulty creating realistic scenarios, integration with existing security processes, and measuring outcomes beyond technical metrics. Their work emphasized the need for cyber ranges to simulate not only technical infrastructure but also business processes and human factors (Vykopal, Ošlejšek, Čeleda, Vizváry, & Tovarňák, 2017).

A study by Chouliaras, et al (2021) surveyed ten Cyber Ranges that were developed in the last decade, with a structured interview (listed in Tables 3 and 4 of their article), documenting how initial enthusiasm for cyber range investments often gave way to utilization challenges when

programs lacked clear governance structures and ongoing executive sponsorship. Their findings suggest that successful cyber range programs require dedicated resources for scenario development and continuous alignment with evolving business priorities (Chouliaras, Kantzavelou, Maglaras, & Pantziou, 2021).

2.5. Emerging Trends and Future Directions

Recent literature points to several emerging trends in cyber range development and application. Artificial intelligence features prominently in current research, with Hatzivasilis, et al. (2020) demonstrating how machine learning can enhance cyber range capabilities through automated scenario generation and adaptive difficulty levels, creating more realistic and challenging training environments (Hatzivasilis, et al., 2020).

The application of cyber ranges to supply chain security represents another frontier. Work by Tam et al. (2022) examined how cyber ranges can simulate complex supply chain attacks, addressing a critical gap in traditional security testing approaches that focus on organizational boundaries. Their case study "Case Study of a Cyber-Physical Attack Affecting Port and Ship Operational Safety" demonstrated the value of cyber ranges in modeling interconnected systems and their vulnerabilities (Tam, et al., 2022).

2.6. Research Gaps and Opportunities

Despite the growing body of literature, significant gaps remain in understanding how organizations can optimize cyber range investments. Most notably, there is limited research on standardized approaches to measuring cyber range maturity and effectiveness across different organizational contexts. Additionally, while technical implementations are well-documented, frameworks for aligning cyber range capabilities with business strategy remain underdeveloped.

Emerging opportunities in cyber range development present promising avenues for research and innovation. The integration of digital twins with cyber ranges offers unprecedented fidelity in simulating organizational environments, as highlighted by Gartner's 2023 report on strategic technology trends (Gartner, 2023). Additionally, Verizon's 2023 Data Breach Investigations Report emphasizes the growing need for supply chain security simulations, creating opportunities for specialized cyber range applications (Verizon, 2023). Furthermore, Yamin et al. (2022) identify the convergence of operational technology (OT) and information technology (IT)

security training as a critical frontier for cyber range evolution, particularly in critical infrastructure sectors where traditional security boundaries are rapidly dissolving.

3. Cyber Range Technology Selection Decision Matrix

Selecting the appropriate cyber range technology is a critical decision that significantly impacts an organization's ability to achieve its cybersecurity training, testing, and research objectives. The decision matrix presented here synthesizes findings from key research including Davis and Magrath (2013), Ukwandu et al. (2020), and Chouliaras, Kantzavelou, Maglaras, & Pantziou, 2021 to provide a structured approach for evaluating cyber range options based on organizational type and specific requirements. This matrix addresses the distinct needs of academic institutions, government agencies, and commercial businesses, recognizing that each sector has unique priorities, constraints, and use cases that influence technology selection.

The framework is built upon empirical evidence from existing implementations and considers multiple dimensions including primary purpose, implementation approaches, cost considerations, scalability requirements, security needs, and customization levels. By mapping these factors against organizational types, decision-makers can more effectively navigate the complex landscape of cyber range technologies and identify solutions that align with their specific operational contexts and strategic objectives. Table 1. Cyber Range Technology Selection Decision Matrix shows the proposed matrix.

Selection Criteria	Academic Institutions	Government Agencies	Commercial Businesses
Primary Purpose	Education and research	Training and operational readiness	Risk reduction and compliance
Recommended Implementation	Simulation (60%), Emulation (30%), Hybrid (10%)	Emulation (50%), Hybrid (40%), Simulation (10%)	Virtualization (70%), Hybrid (20%), Physical (10%)
Cost Considerations	Low to medium budget; focus on educational value	Medium to high budget; focus on fidelity and security	Variable budget; focus on ROI and operational relevance
Scalability Needs	High - must support multiple classes/research groups	Medium - focused on specific agency personnel	Variable - depends on organization size and training needs
Security Requirements	Medium - educational content with some sensitive data	Very high - may include classified scenarios	High - contains sensitive business data and systems
Customization Level	High - must adapt to various curricula and research	Medium - focused on specific agency scenarios	High - must reflect specific business systems and processes
Recommended Technologies	• Open-source virtualization • Cloud-based platforms • Containerization (Docker) • Public/federated architectures	• Dedicated hardware• Specialized simulation tools • Hybrid physical/virtual environments • Private architectures	• Commercial virtualization platforms • Cloud-based solutions • Integration with existing security tools • Private or hybrid architectures
Team Structure	Red-Blue (100%)	Red-Blue-White-Purple (60%), Red-Blue (40%)	Red-Blue (80%), Red-Blue-Green (20%)
Key Success Factors	• Integration with curriculum • Flexibility for various teaching scenarios • Low maintenance overhead • Support for research activities	• High fidelity to operational environments • Robust security controls • Support for complex scenarios • Integration with existing training programs	• Alignment with business risks • Measurable outcomes • Integration with security processes • Efficiency in deployment and operation

Table 1. Cyber Range Technology Selection Decision Matrix

Source: Author has developed

The Cyber Range Technology Selection Decision Matrix reveals important patterns in how different organizational types approach cyber range implementation. Academic institutions typically prioritize educational value and research flexibility, favoring simulation-based approaches that maximize accessibility while minimizing costs. Government agencies, particularly those with defense and intelligence missions, emphasize high-fidelity emulation environments that can accurately represent operational systems, with security considerations being paramount. Commercial businesses tend to focus on virtualization technologies that demonstrate clear return on investment and integrate effectively with existing security processes.

The matrix highlights that while implementation approaches vary across sectors, there is a growing trend toward hybrid solutions that combine multiple technologies to balance fidelity, cost, and operational requirements. Team structures also differ significantly, with government agencies typically employing more complex team configurations that include specialized roles beyond the traditional red-blue team model.

This decision framework provides organizations with a starting point for cyber range technology selection, though specific organizational needs may necessitate customization of the approach. As the cyber threat landscape continues to evolve, the ability to select appropriate cyber range technologies becomes increasingly critical for building effective cybersecurity capabilities across all sectors.

4. A Proposal Roadmap for Cyber Range Implementation

This implementation roadmap provides a structured approach for organizations to establish an effective cyber range capability. Based on the literature review and decision matrix presented earlier, this roadmap addresses the key components necessary for successful implementation: technical architecture, governance framework, staffing requirements, and operational considerations. The roadmap is designed to be adaptable across academic institutions, government agencies, and commercial businesses while acknowledging their distinct requirements.

4.1. Technical Architecture Implementation

4.1.1. Phase 1: Requirements Analysis and Design (Months 1-3)

- **Needs Assessment**: Conduct stakeholder interviews to identify specific training objectives, user profiles, and technical requirements
- **Use Case Development**: Document primary use cases (training, testing, research) with detailed requirements for each
- **Architecture Selection**: Based on the decision matrix, select appropriate implementation approach (simulation, emulation, virtualization, or hybrid)
- **Technology Definition**: Identify required hardware, virtualization platforms, network components, and security tools
- **Scalability Planning**: Design for future growth with modular architecture that can expand as needs evolve

4.1.2. Phase 2: Infrastructure Development (Months 4-7)

- **Core Infrastructure Setup**: Establish server environment, storage systems, and network backbone
- **Virtualization Layer**: Implement selected virtualization technology (VMware, KVM, containers)
- **Network Segmentation**: Create isolated networks with appropriate security controls
- **Security Controls**: Implement monitoring, logging, and access control systems
- **Automation Framework**: Develop scripts and tools for environment provisioning and reset

4.1.3. Phase 3: Content Development (Months 6-9)

- **Scenario Library**: Create initial set of training scenarios based on organizational needs
- **Attack Simulation Tools**: Implement tools for realistic attack simulation
- **Traffic Generation**: Deploy systems to create realistic background network activity
- **Assessment Mechanisms**: Develop scoring and evaluation systems for training exercises
- **Documentation**: Create technical documentation for all components and configurations

4.2. Staffing Requirements

4.2.1. Phase 1: Team Formation (Months 2-4)

- **Core Team Identification**: Define roles and responsibilities for the cyber range team
- **Skills Assessment**: Identify required technical and non-technical skills
- **Recruitment Strategy**: Develop plan for hiring or reassigning personnel
- **Training Program**: Create training program for staff to develop necessary skills
- **External Resources**: Identify consultants or partners for specialized expertise

4.2.2. Phase 2: Team Development (Months 5-8)

- **Technical Staff**: Hire/assign system administrators, network engineers, and security specialists
- **Content Developers**: Recruit staff with expertise in scenario development and instructional design
- **Operations Team**: Establish team for day-to-day management and user support
- **Cross-Training**: Implement cross-training program to ensure operational resilience
- **Continuous Education**: Create professional development plan for ongoing skill enhancement

4.3. Operational Considerations

4.3.1. Phase 1: Operational Planning (Months 3-5)

- **Service Catalog**: Define services offered by the cyber range
- **Capacity Planning**: Establish processes for managing resource allocation
- **Scheduling System**: Implement system for reserving range time and resources
- **Support Model**: Define support levels and response times for different user groups
- **Maintenance Windows**: Establish regular maintenance schedule with minimal disruption

4.3.2. Phase 2: Operational Implementation (Months 6-9)

- **User Onboarding**: Develop and implement user training program
- **Documentation**: Create user guides, FAQs, and knowledge base
- **Feedback Mechanisms**: Implement systems to collect and act on user feedback

- **Performance Monitoring**: Deploy tools to monitor system performance and availability
- **Continuous Improvement**: Establish processes for regular review and enhancement

4.3.3. Phase 3: Launch and Optimization (Months 10-12)

- **Pilot Program**: Conduct limited pilot with select user groups
- **Full Launch**: Roll out to all intended users with appropriate support
- **Performance Evaluation**: Assess technical performance and user satisfaction
- **Optimization**: Refine processes and technologies based on initial experience
- **Roadmap Development**: Create long-term enhancement roadmap based on user needs
- Budget Considerations
- **Capital Expenditures**: Hardware (servers, storage, networking), software licenses, facility modifications
- **Operational Expenditures**: Staffing, training, maintenance contracts, utilities, consumables
- **Contingency Fund**: 15-20% of total budget for unexpected costs and opportunities
- **Funding Models**: Consider subscription-based, pay-per-use, or cost recovery approaches
- **ROI Metrics**: Establish clear metrics to demonstrate value and justify continued investment

4.4. Implementation Timeline

The complete implementation typically requires 10-12 months for initial capability, with ongoing enhancement thereafter. Key milestones include:

- Month 3: Requirements and team formation complete
- Month 6: Core infrastructure operational
- Month 9: Initial scenarios developed and tested
- Month 12: Full operational capability achieved

This roadmap provides a comprehensive framework for implementing a cyber-range capability that aligns with organizational objectives while addressing the technical, governance, staffing, and operational considerations essential for success.

5. Conclusion

This comprehensive project proposal has examined the strategic importance of cyber ranges as essential tools for enhancing organizational cybersecurity preparedness in today's increasingly complex threat landscape. Through a detailed literature review, decision matrix analysis, and implementation roadmap, we have established a framework to evaluate, select, and implement cyber range capabilities aligned with their specific business objectives.

The literature demonstrates that cyber ranges have evolved from primarily military applications to become critical components of enterprise security strategies across sectors. Our analysis of implementation approaches - simulation, emulation, virtualization, and hybrid -reveals that each offers distinct advantages and limitations. The decision matrix we developed provides organizations with a structured approach to selecting the most appropriate technology based on their sector-specific requirements, budget constraints, and training objectives. This matrix addresses a significant gap identified in the literature regarding standardized approaches to cyber range selection and implementation.

The implementation roadmap addresses the practical challenges organizations face when deploying cyber range capabilities. By providing a phased approach covering technical architecture, staffing, and operational considerations, we offer a comprehensive guide that aligns cyber range capabilities with broader organizational security strategies and business objectives.

The business value of cyber ranges extends beyond technical security improvements. As demonstrated through our analysis, properly implemented cyber ranges contribute to enhanced incident response capabilities, improved team coordination, more effective security investments, and ultimately, reduced organizational risk. By providing realistic environments for testing security controls and training personnel, cyber ranges enable organizations to validate their security posture against emerging threats before they materialize in production environments.

Several trends will shape the future of cyber range technologies. The integration of artificial intelligence for automated scenario generation, the growing emphasis on supply chain security simulations, and the development of more sophisticated metrics for measuring cyber range effectiveness all represent promising areas for future research and development.

In conclusion, cyber ranges represent a strategic investment in organizational resilience. By providing a structured approach to their evaluation, selection, and implementation, this proposal offers a valuable framework for organizations seeking to enhance their cybersecurity capabilities in an increasingly complex threat landscape. The framework developed here bridges the gap between technical implementation and business strategy, ensuring that cyber range investments deliver measurable value and contribute to overall organizational security objectives.

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