


Emergency Management of Tomorrow Research: Emergency Operations Center of the Future Recommendations

June 2024

Science and Technology

This report was prepared for the U.S. Department of Homeland Security under a Work-for-Others Agreement with the U.S. Department of Energy, contract DE-AC05-76RL01830, IA 70RSAT23KPM000025.

Pacific Northwest
NATIONAL LABORATORY

PNNL-36082

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U.S. DEPARTMENT OF ENERGY

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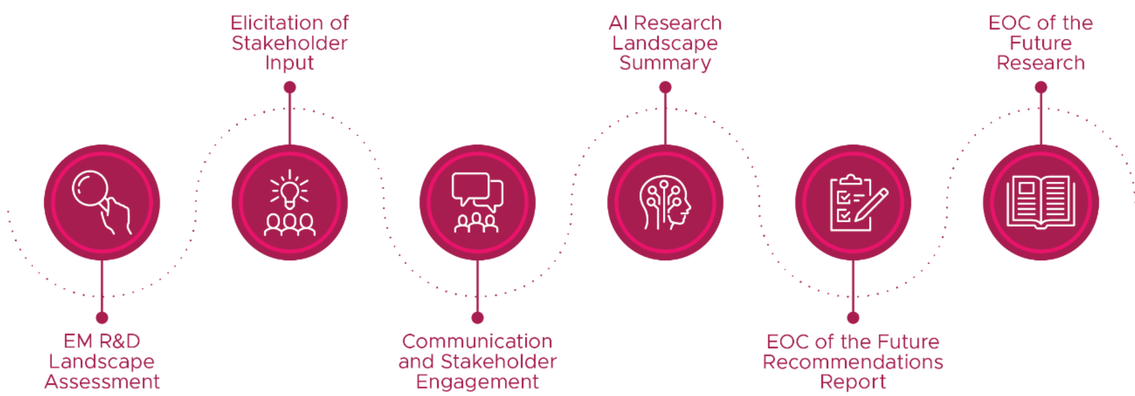
Pacific Northwest National Laboratory
Richland, Washington 99354

About the Emergency Management of Tomorrow Research

The Department of Homeland Security (DHS) Science and Technology Directorate (S&T) is partnering with Pacific Northwest National Laboratory (PNNL) to execute the Emergency Management (EM) of Tomorrow Research (EMOTR) program to conduct research on strengthening and reimagining the future emergency response structure. The EMOTR program is identifying current EM research, eliciting capability needs from EM practitioners, and identifying where technology, such as artificial intelligence (AI), may benefit the future of EM and emergency operations centers. The project is delivering an iterative approach to curating a comprehensive framework to inform future research, development, and investments.[1]

This report details the concepts developed related to the Emergency Operations Center (EOC) of the Future and recommendations to assist DHS S&T in future decision-making. To learn more about this task or others within the EMOTR scope, contact emotr@pnnl.gov.



[1] https://www.dhs.gov/science-and-technology/news/2023/07/26/dhs-st-awards-funds-pnnl-research-future-emergency-management

Summary

As part of the EMOTR program, sponsored by DHS S&T, PNNL developed concepts for the EOC of the Future and is providing recommendations to assist DHS S&T in future decision-making. This task was completed through a landscape assessment of the current state of EOCs and other operations centers, identifying core EOC of the Future concepts, and validating concepts and emerging technology impacts through tabletop exercise experimentation. This task built on previous EMOTR tasks that conducted EM R&D and AI research landscape assessments and elicited EM stakeholder feedback to vet and validate EMOTR results.

By combining previous EMOTR findings with a basic understanding of other operations center domains, foundational concepts for the EOC of the Future emerged, focused on data management, communication, human-machine teaming, physical EOC spaces and systems, and workforce development. PNNL further explored the EOC of the Future concepts through use cases and tabletop exercises, utilizing operational stakeholders to evaluate the potential impacts of emerging technologies on EM operations. This report summarizes all of these inputs, outputs, and exercises into a series of recommendations for a next-generation EOC to inform future research, development, and investment (see Table ES.1).

Table ES.1. EOC of the Future Recommendations

Concept-Based Recommendations	Supplemental Recommendations
• Build a solid data architecture foundation. • Promote continuous awareness and operations. • Develop AI to become an EOC digital teammate. • Meet the needs of the individual operator. • Leverage digital tools to transcend physical boundaries. • Adopt a layered approach to technology integration and EOC functionality. • Crowdsource EM information gathering and response capabilities. • Attract, train, and retain emergency managers of the future.	• Exchange lessons learned with other federal agencies in developing open architecture. • Assess potential cascading impacts of EOC of the Future realization. • Stand up an EM-focused innovation testbed. • Develop an AI-Ready Workforce curriculum. • Create and engage with spaces for students and early-career professionals.

Transcending all of the resulting EOC concepts and recommendations was an emphasis on information sharing and the increasing role of AI. Information sharing will require data sharing agreements, varying dissemination formats and platforms, and information security plans. “Horizontal" sharing needs happen across EOC functions, between private industry and non-governmental organizations, and to the general public. “Vertical” sharing needs happen from a local jurisdictional level, up to a regional level, and finally to a national level, enabling a federated model of EM. AI has the potential to act as an accelerator for each of these concepts. Given the rapid pace of its development in industry, operationalizing AI in EOCs and in EM more broadly will be a significant challenge, particularly if EM is not the primary application.

Based on these trends and recommendations, potential near-term opportunities for achieving EOC of the Future concepts include the following:

- Defining open architecture standards and best practices as a reference guide for local jurisdictions to begin laying the groundwork for data and information sharing.
- Developing operationally secure requirements for deploying AI-enabled productivity applications (e.g., converting situation reports to slides/videos, deconflicting situational awareness information) in EOCs.
- Creating AI and other emerging technology training modules and certifications for EM.
- Engaging more frequently and intentionally with students and early-career professionals on careers in EM and EOCs of the Future.

Acknowledgments

The PNNL team would like to acknowledge appreciation for this work funded through DHS S&T. Additionally, the many participants of the tabletop exercises provided exceptional insights in evaluating the potential impacts of emerging technologies on EOC of the Future concepts. In particular, the PNNL team would like to acknowledge the host cities, organizations, and personnel who helped make these events a success, including Ruhamah Bauman, Jill Misiewicz, Wisconsin Emergency Management, and the Joint Force Headquarters and Wisconsin State Emergency Operations Center; Emily Martuscello and the Dartmouth Hitchcock Clinics from the City of Nashua; and Curry Mayer from the Seattle Office of Emergency Management and the Seattle Emergency Operations Center.

Acronyms and Abbreviations

AI	Artificial Intelligence
BHPD	Beverly Hills Police Department
CIMS	Crisis Information Management Systems
DHS S&T	Department of Homeland Security Science and Technology Directorate
EM	Emergency Management
EMOTR	Emergency Management of Tomorrow Research Program
EOC	Emergency Operations Center
IoT	Internet of Things
ISAC	Information Sharing and Analysis Center
IT	Information Technology
ML	Machine Learning
NIST	National Institute of Standards and Technology
OTAP	Open Threat Assessment Platform
PNNL	Pacific Northwest National Laboratory
PSITC	Public Safety Immersive Test Center
R&D	Research and Development
SOC	Security Operations Center
TTX	Tabletop Exercises

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1.0 Introduction

As part of the Emergency Management (EM) of Tomorrow Research (EMOTR) program, sponsored by the Department of Homeland Security (DHS) Science and Technology (S&T) Directorate, Pacific Northwest National Laboratory (PNNL) developed concepts for the Emergency Operations Center (EOC) of the Future to provide recommendations to assist in future decision-making with regards to research and development (R&D). This effort reviewed the evolution of EOCs amid the recent technological revolution and considered options such as fully virtual EOCs and virtual capacity scaling, the role of autonomous decision-making by artificial intelligence (AI) tools, maintaining situational awareness through advanced communications and geospatial information technologies, advanced display technologies and other emerging future technologies that can increase the effectiveness and efficiencies of EOC in a non-linear manner. Given the growing emphasis on the need for disparate EOCs to share information without impediments, recommendations also focused on the complexity of achieving technology integration and interoperability for information sharing between diverse EOCs and EM operations.

This task was informed by the findings from the major elements of the EMOTR program, as outlined in Figure 1. These activities included conducting an EM R&D Landscape Assessment, eliciting EM and researcher stakeholder feedback, and conducting an AI Research Landscape Assessment (to include mapping EM tasks and functions to AI application opportunities) to identify the current state of research in these respective areas. These efforts informed the development of the EOC of the Future concepts, which provide unique use cases for new and emerging technologies, which were validated through tabletop exercise (TTX) experimentation. Section 5.0 of this report contains recommendations toward the realization of these concepts through technology implementation in future EOCs.

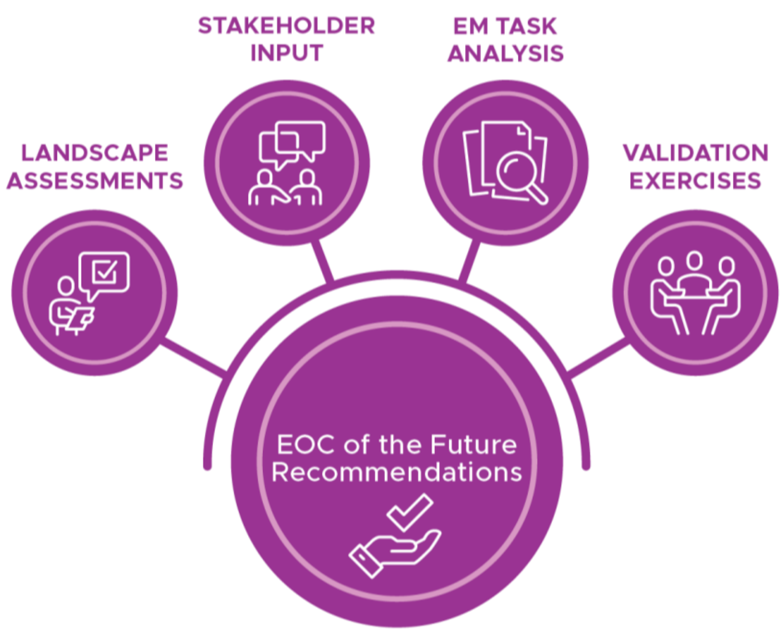

Figure 1. Overview of the EMOTR activities that informed the EOC of the Future recommendations.

2.0 EOC Landscape Assessment

This task began with an EOC landscape assessment to better understand current EM functions and EOC operations and establish a valuable baseline for informing future recommendations. The EOC landscape assessment charted the evolution of EOCs, learning from the way operations centers function in domains outside of EM, and acknowledging their trajectory into the future. This assessment helped shape understanding of emerging technology gaps, capability needs, and R&D priorities, in conjunction with the subsequent EMOTR task findings, to inform development of use cases and TTXs used to validate EMOTR findings (see section 4.0).

2.1 Definition and Evolution

An EOC is a central command-and-control system—either temporary or permanent—where the multi-agency coordination of information and resources normally takes place to support incident or natural disaster responses and short-term recovery efforts.[1,2] EOC functions support the National Preparedness Goal's five mission areas of prevention, protection, mitigation, response, and recovery.[3] Today, EOCs have three primary functions in common:

1. supporting resource needs and requests, including allocation and tracking;
2. coordinating plans and determining current and future needs; and
3. providing coordination and policy direction.

Within each of these functions, core activities include:

- Authorizing EOC activation
- Directing EOC operations
- Gathering and providing information
- Identifying and addressing issues
- Providing internet connectivity and enabling interoperable communications capabilities among partner agencies and organizations
- Response planning and future planning
- Demobilizing EOC management.[4]

EOCs across the nation are incredibly diverse, posing a significant challenge to establishing a framework for a coordinated national approach to EM. They vary in size, population density, socioeconomic, factors, and capacity of resources. In some public, private, or tribal jurisdictions, the EM function is held by one person as one of many roles that they may perform (e.g., public safety). Other jurisdictions can staff several full-time positions. These factors influence an EOC's knowledge and use of new and emerging technologies that can support EM.

[1] DHS. 2017. DHS Lexicon Terms and Definitions: 2017 Edition – Revision 2. https://www.dhs.gov/sites/default/files/publications/18_0116_MGMT_DHS-Lexicon.pdf
[2] DHS. Fusion Centers and Emergency Operations Centers. https://www.dhs.gov/fusion-centers-and-emergency-operations-centers
[3] DHS. 2015. DHS National Preparedness Goal – Second Edition (September 2015). https://www.fema.gov/sites/default/files/2020-06/national_preparedness_goal_2nd_edition.pdf
[4] FEMA. 2022. National Incident Management System Emergency Operations Center How-to Quick Reference Guide. https://www.fema.gov/sites/default/files/documents/fema_eoc-quick-reference-guide.pdf

The physical form of an EOC has evolved significantly over time, and this evolution can be summarized in four generations, outlined in Table 1. Each EOC model is limited in various ways. Before providing a vision for the EOC of the Future, the following section explores several examples of current and future operations centers in adjacent domains.

Table 1. Evolution of EOCs

Generation	Style	Description
First Generation	Cold-Start EOC	The jurisdiction does not have an EOC. If needed, an EOC is quickly established during the incident using a borrowed facility.
Second Generation	Shared-Use EOC	A designated facility that can be quickly repurposed for EOC operations, such as a library conference room. Some upgrades to the shared facility may be made, such as adding phone and internet lines.
Third Generation	Remodeled EOC	The EOC is in a remodeled building. Although the facility might be shared, the primary purpose is that of an EOC. The building's structure and project budget may require some compromises in the design and capability of the EOC.
Fourth Generation	Custom-Built EOC	The facility is designed and built to be an EOC within budget limitations.

2.2 Operations Centers in Other Domains

Similar entities to EOCs exist outside of EM organizations, including watch centers, fusion centers, security operations centers (SOCs), and command-and-control centers, to name a few. In this section, a few examples are provided to highlight current capabilities.

- In June 2022, the Beverly Hills Police Department (BHPD) launched its Real-Time Watch Center, serving as a model for using technology to enhance policing. The watch center is a command hub where police officers fly drones, track license plates, and use other technology to monitor activity across the city. BHPD utilizes virtual patrol officers, including public-private contracted officers from Nastec and Covered 6, to monitor video feeds and direct BHPD officers to crime scenes. BHPD is working toward full situational awareness between the Real-Time Watch Center and units in the field, where every officer will have access to the data feeds they need via their phone or computer.[1]
- The Space Information Sharing and Analysis Center (ISAC) Operational Watch Center was established in 2023 and is supported by a dedicated team of 10 in-person analysts with additional virtual support enabled by cloud architecture.[2] Partnerships with more than 30 government agencies worldwide allow the sharing of threat and vulnerability information, inform policy, and promote joint efforts to secure the global space sector. The Watch Center

[1] Waldinger, J. 2023. "First year of watch center yields lower crime." *Beverly Press*. https://beverlypress.com/2023/06/council-cuts-red-tape-to-build-affordable-units-faster/

[2] *Cloud architecture* dictates how the necessary components and technologies required for cloud computing are integrated to pool, share, and scale resources over a network.

also has a fellowship program to build a diverse and robust talent pipeline for the future through experiential training and other opportunities. Current members of Space ISAC come from a variety of sectors, including AI solutions, machine learning (ML), cloud and data processing, satellite communications, remote sensing, cybersecurity, and more.[1]

- The Alabama Law Enforcement Agency recently deployed a new command-and-control system to support security and tactical operations at Governor Kay Ivey's 2023 Inauguration Day. The system was powered by geographic information system[2] technology to provide a common operating picture and streamline security strategy. Enhanced collaborations between federal, state, local, and private agencies enabled real-time awareness of personnel and operations. The Alabama Fusion Center, a division of the Alabama Law Enforcement Agency, leveraged digital twin[3] technology to guide and improve intelligence collection and threat assessment. As the events of the day unfolded, data was collected and used to plan and refine approaches for future operations.[4]
- An SOC in the private sector is a centralized function or team often focused on security posture and preventing, detecting, and responding to all threats. In the case of cybersecurity threats, most SOCs operate around the clock seven days a week, and organizations with large footprints may also depend on a Global SOC to stay on top of worldwide security threats, coordinating actions across several local SOCs. SOC functions that overlap with EOCs include asset and tool inventory, threat intelligence, log management, incident response, recovery and remediation, and compliance management.[5]

In these few examples, leading capabilities include:

- Virtual operations
- Geospatial analytics and wayfinding
- Situational awareness or common operating picture
- Cloud architecture
- Public-private partnerships
- Multi-sector stakeholders
- Talent development pipeline.

2.3 Additional Perspectives on Future Operations Centers

Given SOC and EOC function overlap, innovations in SOC design and operations can illustrate areas for future growth opportunities in EOCs.

In a 2020 white paper titled "Future of the SOC: Forces Shaping Modern Security Operations," Deloitte and Google Cloud observed that traditional SOC problems over the decades are trying to be solved without accounting for the profound shifts in the landscape that have occurred in

[1] Space ISAC. 2023. "Space ISAC Stands Up Operational Watch Center to Keep Pace with Proliferating Threats to Space Systems." https://spaceisac.org/space-isac-stands-up-operational-watch-center-to-keep-pace-with-proliferating-threats-to-space-systems/

[2] *Geographic Information System (GIS)* connects data to a map, integrating location and various descriptive data to help uncover patterns and relationships in a geographic context.

[3] *Digital twin* is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.

[4] Walter, C., Stowell, K. 2024. "Alabama: Advancing Public Safety with High-Tech Maps and Shared Awareness." *Esri Blog*. https://www.esri.com/about/newsroom/blog/alabama-advances-inauguration-security-with-shared-awareness/

[5] Microsoft. 2024. What is a security operations center (SOC)? *Microsoft Security.* https://www.microsoft.com/en-us/security/business/security-101/what-is-a-security-operations-center-soc

recent years. The role of technology in the 21st century necessitates not just automating repeatable tasks but also automating repeatable cognitive processes. To achieve this, SOCs will be required to develop robust data pipelines and infrastructure with the appropriate speed and scale to process high volumes of data from a diverse set of devices, while remaining vendor agnostic. SOCs should consider how AI can be applied correctly and ethically[1] to serve as an accelerator and empower analysts to perform more meaningful tasks. SOCs are also cautioned against the temptation to be flooded with data sources, tools, and alerts. Some signals may be false, some true but difficult to understand, and some may be operationally irrelevant. Humans will be needed for resolving difficult contexts and for ingenuity. Machines will be needed to deliver better data to humans and improve the quality of alerts across numerous IT environments. The future will rely on humans powered by automation—automation of mundane tasks and automation of decisions—such that humans maintain their focus on the hardest tasks.[2]

Deloitte and Google Cloud followed their 2020 white paper with the 2021 white paper “Future of the SOC – Process Consistency and Creativity: a Delicate Balance.” In it, they built on their prior warning related to the oversaturation of data and tools, noting that security organizations often fall back on existing processes to cope. A high-functioning, modern SOC will likely be balanced between consistency and creativity in its processes. Such processes relevant to EOCs include:

- Automated triage and queue management, which logically process known outcomes and reduce alerts requiring human intervention.
- Agile development of algorithms tuned and managed by operational teams in real-time; near real-time dashboarding.
- Automated risk assessment and resource allocation that changes dynamically as the situation evolves.
- Continuous data collection from network devices.[3]

In addition to AI and automation, *Infosecurity Magazine* wrote about decentralized[4] and democratized[5] SOCs. Single point of failure is a term that represents one piece of a system that, if it fails, will jeopardize the entire system. A decentralized SOC—perhaps virtual or remote—can help mitigate the risk of a single point of failure. Additionally, democratizing SOC functional knowledge, data, intelligence, and decisions—perhaps through a SOC-as-a-Service model (think “SOC in a box” available on demand)—can also help mitigate the risk of a single point of failure. Future operations centers will likely see more public-private partnerships, sharing insights to create a common operating picture and shared situational awareness, which in turn helps to develop whole community action plans to deal with the most significant emergencies.[6]

To summarize, future operations centers should:

[1] *Ethical AI* adheres to guidelines regarding fundamental values, such as individual rights, privacy, non-discrimination, and non-manipulation.
[2] Deloitte, Google Cloud. 2020. “Future of the SOC: Forces Shaping Modern Security Operations.” https://www2.deloitte.com/content/dam/Deloitte/us/Documents/about-deloitte/us-deloitte-google-cloud-alliance-future-of-the-SOC-whitepaper.pdf
[3] Deloitte, Google Cloud. “Future of the SOC: Process Consistency and Creativity – A Delicate Balance.” https://www2.deloitte.com/content/dam/Deloitte/us/Documents/about-deloitte/us-google-cloud-soc-whitepaper.pdf
[4] *Decentralized SOCs* distribute capabilities and core functions across multiple systems and physical locations.
[5] *Democratized SOCs* make capabilities and core functions accessible to all stakeholders.
[6] David, B. 2022. “The SOC Of the Future.” *Infosecurity Magazine.* https://www.infosecurity-magazine.com/magazine-features/the-soc-of-the-future/

- Have a robust data architecture[1] in place to support next-generation capabilities.
- Enable continuous data collection, real-time algorithm tuning, and dashboard updates.
- Leverage AI, with special consideration given to how humans will interact with it to be most effective.
- Account for technology automating tasks, such as triage and queue management.
- Allow technology to automate decisions, such as risk assessment and resource allocation.
- Avoid information overload resulting from too much data, too many tools, and too many alerts.
- Mitigate single-point-of-failure risks through decentralization, redundancy, scalability, and democratization of functions.
- Support whole community action plans through public-private partnerships and shared situational awareness.

3.0 EOC of the Future Concepts

This section summarizes previous EMOTR task work that is relevant to the EOC of the Future discussion. This includes the EM R&D Landscape Assessment as well as EM practitioner perspectives received through interviews, focus groups, and workshops. Combining insights from section 2.0 and other EMOTR activities, this section produces a set of concepts to help define the EOC of the Future.

3.1 Current State of EM R&D

As a foundational task to EMOTR, PNNL conducted a landscape assessment of EM R&D at academic institutions, national laboratories, and other research institutes to curate a comprehensive framework to inform future research investments.[2] The EM R&D Landscape Assessment surveyed recent research (2017-2023) in EM and public safety to create an annotated bibliography that highlights areas for potential collaboration and common interests within EM research.

PNNL identified two priority capability gaps related to EOCs that warrant further investigation:

- A lack of scalability and interoperability[3] of current information management systems
- Underrepresentation of the need for information technology (IT) professionals in the EOC

Information management systems are used to improve the common operating picture and situational awareness among responders and responding agencies. Current systems are particularly pushed to their limits in the face of large-scale events with multi-jurisdictional responses that require the activation of mutual aid agreements. R&D to support information management system improvements must be scalable, flexible, easy to use, accompanied by sufficient operator training, and interoperable with existing systems and between agencies.

[1] *Data architecture* defines how data is collected, managed, distributed, and consumed.
[2] Sleiman, C., Thomas, K., Gray, J. Schroeder, J., Disney, M., Alsabagh, H., Ortega, S., Bartholomew, R., Lesperance, A. (2024). "Emergency Management of Tomorrow Research Landscape Assessment." Pacific Northwest National Laboratory. PNNL-35649
[3] *Interoperability* refers to the ability for systems to exchange and make use of information such that disparate systems can operate in conjunction with one another.

Studies from primarily academic institutions state the current information management systems used to coordinate large-scale events do not meet the needs of the responding communities.

Given the continued proliferation of new and emerging technology throughout society, a troubling finding from the research indicated a lack of partnerships between the EM community and IT and telecommunications professionals. These operational silos may likely contribute to communication and data integration challenges in EOCs. A partnership between EM operators and IT and telecommunications professionals would support the identified gaps of operator uncertainty and lack of training in systems.

PNNL also identified overlap or opportunities for collaboration in research topics within:

- Social media analytics
- AI/ML
- Community resilience
- Satellite technology
- Emergency response solutions to power grid issues
- Evacuation response
- Smart City applications and informatics ecosystems
- Critical infrastructure damage assessments.

The landscape assessment and annotated bibliography are available by request to emotr@pnnl.gov.

3.2 EM Community Engagement

As part of the EMOTR program, PNNL also conducted a multi-part task to elicit input from the EM stakeholder and research communities in a collaborative and interactive way, as shown in Figure 2. The task comprised a series of structured engagements designed to elicit stakeholder feedback on EM-related technologies and operations, discuss how they are evolving, and gather operational and researcher perspectives on how they might impact incident management. Engagements were guided by previous and concurrent tasks conducted as part of the EMOTR mission to assess current research in the field of EM, elicit capability needs from EM practitioners, and identify where technology, such as AI, may benefit the future of EM and EOCs. Detailed reports from each engagement (interviews[1], focus groups[2], and roundtables[3]) are available by request to emotr@pnnl.gov.

EM and EOCs are poised to experience significant transformation driven by advancing technology, evolving societal needs, and lessons learned from past events. Through conversations with EM personnel and stakeholders (including researchers, operators, and emergency managers), key trends emerged as PNNL navigated outreach to establish a baseline understanding of information sharing, the effectiveness of current research in closing EM capability gaps and fostering a dialogue with EM research stakeholders to encourage collaboration. The following section summarizes feedback from EM personnel and themes

[1] Ortega, S.R., M.V. Disney, C.M. Sleiman, R.A. Bartholomew, A.M. Lesperance, J.L. Barr, and J. Gray, et al. 2024. *Emergency Management of Tomorrow Research – Current State of Practice: Information Sharing*. PNNL-35727. Richland, WA: Pacific Northwest National Laboratory.

[2] Ortega S.R., M.V. Disney, C.M. Sleiman, N.J. Betzsold, R.A. Bartholomew, A.M. Lesperance, J.L. Barr, and J. Gray. 2024. *Emergency Management Research and Development Community Awareness*. PNNL-35880. Richland, WA: Pacific Northwest National Laboratory

[3] Ortega S.R., M.V. Disney, C.M. Sleiman, N.J. Betzsold, A.M. Lesperance, R.A. Bartholomew, J.L. Barr, and J. Gray. 2024. *Emergency Management Research and Development Community Coordination*. PNNL-35996. Richland, WA: Pacific Northwest National Laboratory.

reflecting what practitioners and researchers believe the future of EM and EOCs will look like, envisioning a dynamic blend of hybrid, in-person, and virtual operations within EOCs, with the role of EMs evolving in response to the changing threat landscape. Detailed reports summarizing EMOTR outreach and stakeholder elicitation are available by request to emotr@pnnl.gov.

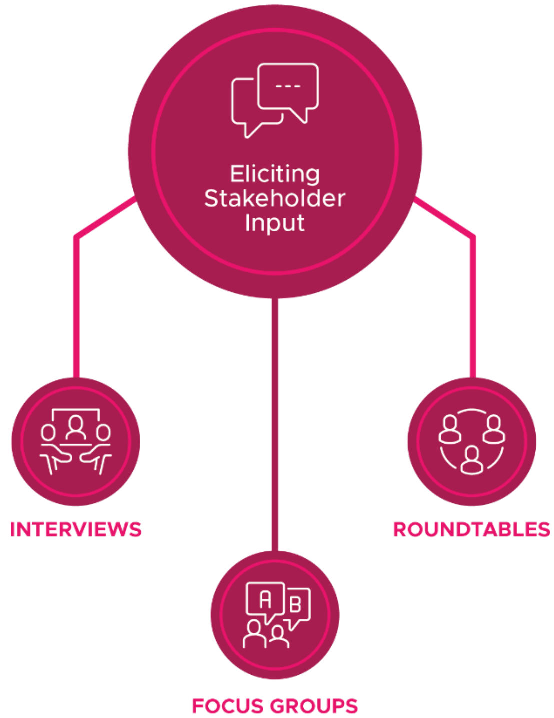

Figure 2. PNNL connected with EM personnel to elicit input on EM R&D.

3.2.1 Technology and Technical Capabilities

According to EM personnel interviewed, the seamless integration of data analytics and AI will be paramount. The expectation is that EOCs will need to harness real-time data streams from various sources, including sensors, social media, and satellite imagery, to enhance situational awareness and facilitate rapid decision-making. Practitioners mentioned using AI algorithms to assist in forecasting incident patterns and behavior, optimizing resource allocation, simulating scenarios to test response strategies, and even as digital assistants to help inform decision-making.

3.2.2 Structure and Organization

EM personnel shared that they anticipate a shift toward more decentralized and resilient EM frameworks. Instead of relying solely on centralized EOCs, networked approaches will be needed with distributed command centers and hybrid/virtual EOCs. These decentralized nodes will be interconnected through robust communication systems, enabling interoperability among different agencies and jurisdictions. These approaches will enhance flexibility and scalability, enabling a faster, more adaptive response to dynamic and complex incidents.

3.2.3 Policy and Operations

While envisioning the EOC of the Future, several key themes emerged, primarily focused on enhancing information sharing, resource management, and situational awareness, which includes establishing robust (and possibly automated) validation processes for information, developing platforms for rapid and efficient resource allocation, and creating protocols for seamless and secure information exchange across government entities. Overcoming barriers such as funding limitations and policy constraints, enhancing trust in new systems and AI, and balancing human-machine interactions to optimize decision-making is crucial. Other topics emphasized included leveraging existing technology like WebEOC (with modifications) and exploring AI solutions for planning, data analysis, and decision support.

3.2.4 Emergency Management Research

EM-focused research personnel reflected on the future of EM research initiatives and highlighted several challenges and opportunities. Challenges emerged in addressing misinformation on social media, maintaining data integrity and network security for AI/ML applications, and filling gaps in human-centric research for emergency response personnel. On the technology front, emphasis focused on leveraging AI and ML for incident detection and communication improvement, including exploring applications in security and network analysis. However, challenges persist regarding data availability, particularly in the private sector, where access is restricted. Current research strategies include further R&D efforts in emerging technologies like AI/ML, cloud solutions, unmanned aerial systems, and human-centric approaches to EM, along with integrating cybersecurity and enhancing testing mechanisms, particularly in real-world emergencies. These efforts aim to enhance the adaptability and effectiveness of EOCs in handling future crises and are not all-encompassing of the current state of research in EM.

3.3 Resulting EOC of the Future Concepts

Combining the themes from the EM R&D Landscape Assessment and stakeholder input (sections 2.2, 2.3, 3.1, and 3.2) resulted in foundational concepts for the EOC of the Future, outlined in Table 2 and described in detail below.

Table 2. EOC of the Future Foundational Concepts

EOC of the Future Foundational Concepts	
• Next-generation data management	• Hybrid EOC operations
• Continuous, real-time situational awareness	• Resilient system design
• AI automation and human-machine teaming[1]	• Whole community approach
• Human-centered design of workspaces	• Forward-leaning workforce development

3.3.1 Next-Generation Data Management

The goal of any EOC during an incident is to develop actionable information and intelligence. The EOC of the Future will only be as effective as the data foundation allows. Traditionally siloed, jurisdictional data come with varying policies, privacy, and overall structure. To maximize their effectiveness, data sharing agreements must be put in place such that these volumes of disparate data can be fused without impediment, through robust data pipelines and infrastructure architected with the appropriate speed and scale. Data pipelines need to run both horizontally and vertically—across public and private organizations and across federal, state, local, and tribal agencies—to truly establish a framework for a coordinated national approach to EM.

The volume of data will only increase as continuous, real-time data collection modalities are added. Cloud architecture, data fabric[2], and data mesh[3] technologies are foundational elements

[1] *Human-machine teaming* refers to the way in which humans collaborate and interact with technologies as they both perform functions toward achieving a common goal.
[2] *Data fabric* facilitates efficient identification of needed data inputs and construction of data pipelines to create necessary products from pooled data.
[3] *Data mesh* maintains distinct data sources aligned by function but still efficiently manages the associated (and sometimes differing) rules and regulations for the common greater good.

of this concept. Additionally, AI approaches that depend on large datasets may require synthetic data to supplement some sources that may be lacking or difficult to obtain.

3.3.2 Continuous, Real-Time Situational Awareness

Traditional situational awareness reports written every few hours are at risk of being out of date before they are published and must evolve to keep pace with the rate at which data, information, and intelligence are developed and disseminated. EOCs will need to harness real-time incident data, information, and intelligence streams from various sources, such as sensors, social media, satellite imagery, and Internet of Things (IoT) devices.[1] This must seamlessly be shared across EOC functions.

In addition, staff are often overwhelmed by the volume of data, information, and intelligence they must sort through, which is expected to increase. AI systems can help to overcome this problem, influencing factors of incident management such as:

- Geolocation of all available (and potentially available) resources
- Optimal routing of resources
- Capacity and processing capabilities of resources (e.g., accurately forecasting task completion based on variables such as environmental data, team skillsets, and physiological data).

Geospatial analytics[2], geolocation, and wayfinding capabilities are included under this concept. Continuous, real-time situational awareness will need to be digestible in a variety of formats (e.g., text, audio, visuals) and on a variety of platforms (e.g., command center, desktop, mobile device). Situational awareness also must be conveyed in harmony with the competency of the personnel receiving it (i.e., operations manager versus epidemiological scientist). This model will necessitate a change in how incident action plans are created to support planners with the ability to almost instantly consider a range of future operational objectives and associated outcomes. Modeling and simulation can help facilitate situational awareness transitions between steady-state and emergency operations.

3.3.3 AI Automation and Human-Machine Teaming

No set of future concepts is complete without the acknowledgment of AI. AI has the potential to automate and enhance many routine and repetitive functions of an EOC. Additionally, some of the most challenging problems faced during an EOC activation become more tractable as AI and humans are effectively integrated as teammates. AI can act as an accelerator, taking on tasks such as planning, data collection, data analysis, predictive modeling—even serving as a digital personal assistant to handle writing emails, messaging to the public, developing presentations, or maintaining contact and inventory lists. EOC personnel are empowered to perform more meaningful tasks as AI becomes a decision-support tool, deconflicting information, designing and optimizing strategies, and discovering potential cascading impacts. Through seamless integration across data streams and autonomous systems, AI enables sustained operations during long and simultaneous events.

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[1] *IoT devices* are everyday devices that can transmit/receive a signal/data (e.g., Wi-Fi, Bluetooth, wireless network).
[2] *Geospatial analytics* factor in elements of space and time, enabling the identification of new patterns related to distance/proximity, density in a region, and shifts over time.

AI is unlike any technology EOCs have encountered. It will require staff to learn new skills, ask the right questions, have the ability to evaluate the AI performance, oversee that AI is properly configured to support EOC operations, and more. AI will also add pressure on EM staff and managers to properly train EM personnel and integrate AI into operations. Governance will need to be established to inform who owns and maintains various individual AI systems as well as how different AI systems will interact with one another to support an incident (including conflict resolution). AI is expected to continue to improve at a rapid and accelerating pace for the foreseeable future. Keeping pace with these EOC advancements will be a significant challenge, particularly if AI is not developed for EM from the start (i.e., industry trains AI models for business applications and transfers to EM functions versus AI models being trained on EM data throughout the entire AI training and testing life cycle).

3.3.4 Human-Centered Design of Workspaces

The vast quantities of data, information, and intelligence that the previous concepts produce and facilitate need to be optimized for individual, functional consumption. This means that each person in the EOC receives only what they need for their assigned role, avoiding cognitive overload. In addition, how these insights are organized and presented is tailored to the preferences and abilities of each EOC operator, based on human factors research, to maximize productivity and minimize fatigue. AI knows each operator's preferences and adapts accordingly. Customizing information extends beyond the EOC staff to everyone involved in the response, from the field to the federal agencies miles away. Additional technologies to support tailored workspaces include advanced display technologies such as dashboards, augmented and virtual reality[1,2], and digital twins.

Additional research will be needed to create a customized AI experience for each EOC staff member. While much work has already been done to identify the essential elements of information for most positions in the EOC, every incident and its associated essential elements of information is different. As noted previously, each EOC is unique in how they are staffed and organized requiring yet more customization of the AI.

3.3.5 Hybrid EOC Operations

In the EOC of the Future, the number of staff needed to manage the incident is not constrained by the size of the EOC facility. Instead, EOC personnel from within the impacted jurisdiction or from across the country mobilize and are on scene virtually within minutes, enabling rapid EOC activation. This hybrid model eliminates two common problems in EOC operations: sufficient staffing and the ability to sustain that staffing 24/7 over weeks or even months. A hybrid approach can draw upon the entire nation of trained and experienced EOC personnel and subject matter experts.

The vision for a hybrid-operating EOC is an environment where coordination, collaboration, and communication are seamless, regardless of where personnel are located. Notably, EOCs ordinarily work closely with partners in other locations such as incident commands in the field, department operating centers, agencies in different jurisdictions, and supporting EOCs. However, the current model that supports such partnerships is limited in both its capacity and its ability to enable robust teaming in the dynamic environment of a major incident. This was illustrated in the attempts by many EOCs to operate virtually during the COVID-19 pandemic. A

[1] *Augmented reality* is a technology that superimposes a computer-generated image on a user's view of the real world.
[2] *Virtual reality* is the computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way.

hybrid EOC model would support, not replace, the current hierarchal (local, state, federal) response doctrine under the National Response Framework[1] via allowing teaming by function instead of jurisdiction. For example, individuals at different levels of government responsible for logistics could work in the same virtual room.

Decentralizing the EOC is also a safeguard against a single point of failure—if a piece of functionality goes down during an incident, it can more readily be replaced by the next available resource. A hybrid EOC model provides increased flexibility and scalability. Robust, advanced communication systems (e.g., 6G, satellites) and network architecture (e.g., cloud), as well as interoperability requirements, will be critical to supporting this concept. Processes and procedures will need to be developed, best practices identified, and exercises conducted to develop guidance for conducting hybrid EOC operations during an incident within one EOC or with multiple EOCs providing support. The lessons learned from the COVID-19 pandemic response can serve as a starting point. EOCs will need to cross-train the virtual mutual aid EOC personnel. This will require designation of mutual aid EOCs prior to the incident that best aligns with the requesting EOC. Factors in the selection of virtual mutual aid EOCs should include:

- Common hazards (e.g., jurisdictions that respond to tornadoes)
- Similar EOC organizational structure
- Comparable jurisdictions (i.e., culture, demographics, population, size and type of government, capabilities)
- Location outside the expected impact area
- Similar technological capabilities, including incident management software.

Technologies to support hybrid operations will need to be developed and tested. Robotics provides a new approach to virtual operations with mutual aid EOC staff occupying robots located in the requesting EOC. The Emergency Management Assistance Compact is a mutual aid agreement among U.S. states and territories that provides a mechanism for authorizing and conducting mutual aid assistance between states. To enable rapid activation of virtual EOC mutual aid, agreements will need to be put in place before an incident occurs. AI assistance will be needed to bridge the gap in knowledge by mutual aid EOC personnel about the local environment, capabilities, and resources. Even with prior training, personnel will need help working in a new EOC until they are oriented.

3.3.6 Resilient System Design

An increased digital footprint in the future also results in an increased cyber-attack surface. Challenges in addressing misinformation on social media as well as maintaining data integrity and network security for AI applications will continue. Future EOCs need to be architected with several layers of redundancy, to include out-of-bounds networking—disconnected networks containing copies of live networks that can be utilized should the live networks be compromised and shut down—and multiple data sources feeding each core EOC function. Redundancy also validates data, information, and intelligence coming into the EOC and reduces single-point-of-failure risk. A critical tool in fostering trust and buy-in from all data and information sharing stakeholders will be the creation of information security plans.

[1] DHS. 2019. National Response Framework – Fourth Edition (October 2019). https://www.fema.gov/sites/default/files/2020-04/NRF_FINALApproved_2011028.pdf

Redundancy supports scalability across rural and urban jurisdictions as well as jurisdictions with varying resources. Core EOC functions can exist in every jurisdiction, albeit with varying capabilities. For example, a low-tech jurisdiction can maintain a basic resource allocation function through manual data entry into a spreadsheet, while a high-tech jurisdiction may have access to multiple data feeds providing live inventory information and AI assistance to optimize decisions. The capability level can be summarized by metrics such as confidence scores, where increased redundancy, data, and overall capability will result in greater confidence in the decisions being recommended to each function. If a portion of the high-tech jurisdiction's resource allocation function were to be compromised, redundancy would maintain the resource allocation function but at a reduced confidence.

3.3.7 Whole Community Approach

The focus of National Incident Management System guidance is directed toward "enabling the participation in incident management activities of a wider range of players from the private and nonprofit sectors, including non-government organizations and the general public, in conjunction with the participation of all levels of government to foster better coordination and working relationship."[1] The uncertainty of budgets to purchase and sustain business poses risk to the private sector developing and investing in tools for state and local EM given. Realizing the benefits of shared situational awareness and pooled resources to respond to emergencies calls for additional efforts requires increased coordination and collaboration.

As technology advances, people are more connected than ever. An effective EOC of the Future will leverage data, information, intelligence, and personnel beyond traditional sources, to include private industry, non-governmental organizations, and the general population. This creates an "EM at the edge" environment in which anyone with a connection can contribute to the response. Power in numbers is magnified as diversity increases, to the benefit of policy development, information exchange, and shared situational awareness.

AI will provide an unprecedented capability to work with the community during the incident. This will require:

- Analysis of large amounts of data, information, and intelligence from the community that has previously not been available. This includes treating every community member as a possible responder.
- Incorporating community-based data, information, and intelligence into the incident's situational awareness and then sharing that analysis with the community.
- Monitoring community performance in conducting missions.
- Identifying and tracking community resources and capabilities that may be difficult to characterize and are not always available on a predictable schedule.
- Modifying incident action planning processes to incorporate community resources. Tasking of and communicating with community resources could potentially overwhelm operations and will likely require extensive support from the AI.
- Significantly automating the interaction between community resources and EOC and Incident Command Systems. This will include measures to assess mission risk and provide for the safety of all concerned.

[1] https://www.fema.gov/sites/default/files/2020-07/fema_nims_doctrine-2017.pdf

3.3.8 Forward-Leaning Workforce Development

Emergency managers of tomorrow will look, think, and act much differently than emergency managers of today. Gen Z (born 1990s to 2000s) has grown up in the age of smartphones and a post-9/11 society.[1] Gen Alpha (born 2010-present) will experience hybrid and virtual classrooms as the norm post-COVID-19 and will grow up in the age of AI.[2] As emerging technology is increasingly integrated into EM, existing jobs and skillsets will become redundant or irrelevant, but demand for new jobs and skillsets will emerge. For example, ChatGPT and other AI tools that require prompts from humans are only as good as the prompts they receive. This is creating the need for skilled prompt engineers. The EOC of the Future will depend on acquiring talent that has technological proficiency but is also familiar with EM. This will come through targeted engagements with younger generations and adopting training curricula that emphasize the utilization of emerging technologies.

4.0 EOC of the Future Concept Refinement

The preceding section highlighted concepts with several enabling and emerging technologies resulting from analysis of the EM R&D Landscape Assessment[3] and stakeholder outreach. PNNL performed an additional landscape assessment of AI technologies and their potential application to EM.[4] Through extensive literature review and validating discussions with emergency managers, as well as input from PNNL subject matter experts, several technologies were identified as likely to significantly impact EM in the next 10 years. This section outlines several potential use cases for these technologies in an EOC of the Future, along with additional details and EM examples, outlined in Table 3. These tools are defined in Appendix A. The use cases provided an approach to refining the EOC of the Future concepts into final recommendations.

Table 3. EOC of the Future Technologies

EOC of the Future Technologies	
• AI • IoT devices • Cloud, fog, and edge computing • Data fabric and data mesh • Robotics and autonomy	• Situational awareness tools: digital twins and geospatial analytics • Social media analytics • Advanced wireless communications • Augmented and virtual reality • Predictive analytics

[1] https://www.britannica.com/topic/Generation-Z
[2] https://www.britannica.com/topic/Generation-Alpha
[3] Sleiman, C., Thomas, K., Gray, J. Schroeder, J., Disney, M., Alsabagh, H., Ortega, S., Bartholomew, R., Lesperance, A. (2024). "Emergency Management of Tomorrow Research Landscape Assessment." Pacific Northwest National Laboratory. PNNL-35649
[4] Barr, J., Hagen, A., Tietje, G., Betzsold, N., Greer, A., Best, E. (2024). "Emergency Management of Tomorrow Research – Artificial Intelligence Landscape Assessment." Pacific Northwest National Laboratory.

4.1 Emerging Technology Use Case Assessment

PNNL conducted a deeper dive into the technologies impacting EOC of the Future concepts by developing use case applications for further exploration. The result was a set of TTXs designed to assess the impacts and benefits of emerging technologies on EM organizations. This section describes the themes and approach utilized in the TTX facilitation. Section 4.2 provides a high-level summary of the three TTXs

Each TTX sought to evaluate the potential impacts of new technologies on EM operations, including:

1. identifying technologies that could improve EOC response operations;
2. listing efficiencies gained and performance enhancements in EOC operations through the use of the identified technologies;
3. discussing limitations, concerns, and mitigation strategies for the identified technologies; and
4. reviewing how to implement the identified technologies.

The TTXs brought together emergency managers and first responders with diverse backgrounds; federal, state, and local EOC stakeholders; and academic researchers. Participants were not expected to solve the incidents presented in the TTX scenarios. Instead, the exercises sought to jump-start discussions about the technologies, data inputs, tasks, coordination, outputs, and gaps between the current and desired future states. Participants were coached to keep discussions broad and focused on the impacts of technology on a given scenario.

The TTXs were designed to be sequential, spanning a variety of EM organization sizes and population densities:

- **An EM organization in the Midwest.** Technologies such as AI and the virtual or hybrid EOC operations concept—which relies heavily on efficient communication and distributed capabilities from county, state, and federal organizations—were presented to focus discussion on technology supporting EM personnel.
- **An EM organization covering a sprawling suburban environment.** Human-machine teaming was presented to focus discussion on how the most useful emerging technologies and tools can be optimized for maximum EM function effectiveness.
- **An EM organization in a large city with the capability to employ the most effective technologies and tools for automation.** Enhanced community partnerships during disaster response—a whole community approach or “EM at the Edge”—and how emerging technologies can facilitate this concept were the focus of the discussion. Discussions sought to identify ways to maximize efficiency in EM awareness and response when circumstances are overwhelming.

Against this backdrop, each TTX was facilitated around an extreme, futuristic emergency scenario with a technological complication, such as a cyber-attack. Figure 3 summarizes the TTX framework (the threats, complications, and themes). In the scenarios, TTX participants identified routine tasks and major problems they would encounter in the EOC during response. Next, exercise facilitators presented several technologies for evaluation by the participants. The evaluation focused on how effectively the technologies addressed the problems as well as the feasibility of applying the new and novel technologies to support EOC functions.

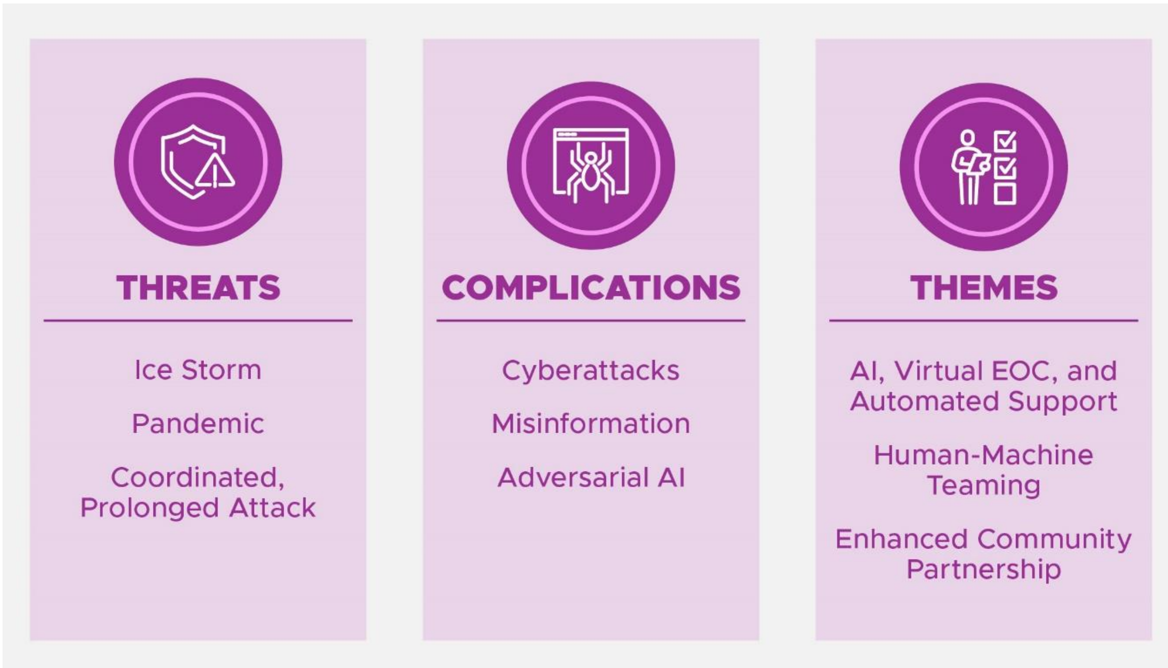


Figure 3. Tabletop exercise framework.

4.2 Emerging Technology Use Case Experimentation

TTX events were held in Madison, WI (Figure 4); Nashua, NH (Figure 5); and Seattle, WA (Figure 6). The TTX summaries in this section highlight the scenario presented and the key discussion points from each event. Inputs and analyses are included without attribution of individual participants to maintain anonymity and encourage open dialogue. Details from the specific events are featured in individual summary reports available by request to emotr@pnnl.gov.

4.2.1 Madison, WI (March 28, 2024)

Scenario: A typical winter storm takes a turn for the worse as snow and ice trap people in their homes for days, essential supplies run low, and road crews struggle to clear roads to grocery stores and homes fast enough. Widespread power outages have only made matters worse. The National Guard has been activated and begun deliveries of fuel and food and providing transport to shelters. Already, posts on social media are calling the response too slow and a failure. People are asking why the power restoration seems to prioritize wealthy neighborhoods. To make matters worse, adversaries have successfully launched

Figure 4. Christina Bapst-Stump of DHS S&T kicks off the Madison TTX.

cyber-attacks against infrastructure that would normally be resilient to such a situation. The city accounting department has been unable to pay employees and personnel records have been posted on the web. Not all EOC personnel can get to a physical meeting location.

Discussion Summary:

- AI should help uncover the unknown information associated with an incident (e.g., anomaly detection).
- Data sources utilized by AI matter. Closed or validated sources improve trust in AI, but this must be balanced with the open or unvalidated sources that are potentially left out.
- It is necessary to understand who should receive which messages, how to tailor the messaging according to language/culture, and in what way the messages will be most likely to be consumed.
- Much historical data on similar events, including developed plans, goes unutilized because of the high-stress demands of an unfolding emergency. AI can help remedy this and support redundancy efforts by helping fill the institutional knowledge and situational awareness gap when EOC functions go down, particularly in a virtual or hybrid EOC environment. AI can also help de-conflict various response plans and aggregate after-action reporting into a cohesive story.
- Emerging technology has a side effect of creating demand for new skills. For example, ChatGPT and other AI tools that require prompts from humans are only as good as the prompts they receive, thus creating the need for skilled prompt engineers.
- Situational awareness is built and maintained during normal operation, not only during emergency incidents. EM personnel need tools they can use during emergencies and non-emergencies.
- Increased reliance on technology should not have the unintended consequence of losing root-cause understanding of emergency events.
- It is not clear whether AI-generated materials (notes, emails, plans, etc.) carry the same legal weight as those created by human personnel. Ultimately these are tools, and tool operators need to be appropriately trained to assume the liability for decisions made based on tool outputs and recommendations.

4.2.2 Nashua, NH (April 10, 2024)

Scenario: The next global pandemic has struck. Local EM is utilizing the latest, state-of-the-art technologies and AI to assist in its functions. The comprehensive set of IoT devices and AI tools has provided malicious actors with a larger attack surface for adversarial AI. A group suspected to be responsible for the creation of the virus is covertly manipulating data and disrupting sensing systems and algorithms. At the height of the first wave of hospitalizations, an IoT attack is launched, interfering with medical devices. In addition to responding to the pandemic, EM personnel must evaluate their ability to effectively team with the technology available.

Figure 5. PNNL-DHS team at the Nashua TTX.

Discussion Summary:

- Relevant tasks and functions include data collection, developing incident action plans, training units, updating distribution/inventory/contact lists, staffing, situational awareness, communications, verifying/deconflicting information, resource allocation, action prioritization, handling constantly evolving requirements, managing cascading impacts.
- A Situational Awareness Virtual Assistant (“Sit Bot”) maintains a continuous common operating picture, personalized to individuals, understands that not everyone is up to date at all times, and can also be used during steady-state operations (not just in an emergency).
- Maintaining accurate contacts, staffing, etc. is a byproduct of a more foundational data management capability. What will these information sharing systems touch? Who will have access and to how much?
- Situational awareness functions include searching, monitoring, filtering, collecting, parsing, integrating, aggregating, disseminating, classifying, etc.
- Misinformation and disinformation are such difficult challenges because of the varying levels of malicious intent behind each one. Where the information is originating from, who the information is targeting, and why, are all useful factors for contextual understanding.
- Messaging should convey a single, common idea that is delivered in the most tailored way for each distinct audience.
- Virtual EOCs must also work for personnel who may have asymmetric levels of virtual capabilities.
- Dedicated EOCs are essentially wasted space when personnel are not actively managing emergencies (which is most of the time). This creates the need for an “EOC in a box,” where the various concepts and technologies that are needed to respond to a given emergency are easily deployable and quickly available when needed.
- Tasks should be evaluated and prioritized for automation or AI based on value added to EOC operations, not simply because they can be automated or aided by AI.
- Tools such as AI should support merit-based processes and outcomes.

4.2.3 Seattle, WA (May 9, 2024)

Scenario: At 1200 hours on a Monday, 9-1-1 receives reports of several separate groups—armed with AK-47 rifles and explosives and wearing body armor—driving and walking through the greater downtown area, attacking pedestrians and drivers. A series of running gunbattles take place over several hours. A school, city hall, one large electrical substation (causing a power outage to a portion of the city), and the level 1 trauma center are attacked. After several hours, multiple attackers have been killed or captured. However, as night falls, at least two groups or several individuals are thought to be in the area. A curfew is established, and all businesses and schools are

Figure 6. PNNL's Nick Betzsold kicks off the Seattle TTX event.

ordered to close. A city-wide search is underway. Several officers and firefighters have been wounded or killed. An estimated 30 people have been killed and over one hundred wounded. Mutual aid continues to pour into the city and the National Guard has been activated.

Discussion Summary:

- Information needs to be collected and consolidated as much as possible; however, concerns persist regarding trusting access controls, the inputs to AI algorithms, and the outputs (decisions) from AI. This is a dynamic (not static) issue, with the “right” approach to handling these concerns likely shifting and evolving over time.
- Technology should communicate like a human to help increase trust. Can a machine teammate be trusted and interacted with like a close friend? Can a machine be trained to understand need-to-know?
- Expanding virtual or hybrid EOC resources raises concerns with span of control. It is great to have increased redundancy and availability of resources, but management challenges also increase.
- Learn from the private sector for capabilities such as supply chain management to become more self-reliant.
- Public-private partnerships need better give-and-take—possibly in the form of data sharing or decision-making—from both parties.
- Community engagement begins with building relationships.
- Whole community approaches should encourage diversity of all kinds, but particularly from youth. Young adults are flying drones, growing up with AI, and they understand how technology can be applied in a variety of settings. Youth engagement can start with universities but should not be afraid of younger generations.
- Training can be improved for EM personnel as well as volunteers. Systems should be put in place that can streamline background checks, leverage volunteers’ skillsets they choose to share, and provide just-in-time training for a given incident.

4.3 Key Findings and Implications for the EOC of the Future Recommendations

The TTXs produced valuable insights that impacted the final set of recommendations. The two most prevalent themes of TTX discussion centered around information sharing and AI in EM.

With the many organizations that bring data to decision-makers in an EOC, the data architecture must span EOC functions, private industry, non-governmental organizations, the general public, and a variety of jurisdictional levels. Data governance (i.e., standards and/or policies) need to provide access control and help prevent corruption from misinformation and disinformation. As disparate data are fused for greater contextual understanding, data and insights can be shared with the appropriate audience, in the right format and with the right timing to maximize the likelihood of the optimal action being taken.

TTX participants identified several routine, repetitive, yet time-consuming EM tasks that are ripe for automation through emerging technology such as AI. Improved information sharing paired with AI will enhance the capacity of the EOC (speed and scale) through simple things like utilizing historical data and deconflicting data sources. As the tasks that AI is permitted to take on increase in complexity and consequence, EOC personnel will not feel empowered to take on more meaningful responsibilities unless they can trust the AI. Trust will be built through transparency, human-machine teaming, and success, and it will improve greatly by developing AI with EM as the primary application, not secondary.

These takeaways and more led to the final set of EOC of the Future recommendations contained in the following section.

5.0 EOC of the Future Recommendations

By exploring the EOC of the Future concepts and emerging technologies through landscape assessments, stakeholder input, use cases, and TTX activities, PNNL identified several opportunities, outlined in Table 4 and Table 5. These recommendations are intended to help strengthen and reimagine the future emergency response structure in EOCs, informing future R&D and investment toward establishing a framework for a coordinated national approach to EM. The recommendations are outlined in three components: Emphasis Area, Value Adds, and Enabling Tools, which are defined as follows:

- Emphasis Area is a high-level description of the recommendation.
- Value Adds is a list of the major gains that could result from pursuing the emphasis area, sorted in a manner that accounts for potential dependencies and increasing levels of complexity.
- Enabling Tools is a list of more prominent technologies that pair with the emphasis area and contribute to the value adds.

See Appendix A or the AI Research Landscape Assessment (available separate from this report) for detailed descriptions of these enabling tools.[1] Notably, policy development will be associated with each of these emphasis areas to facilitate the successful transition to an EOC of the Future; policy needs or implications are not addressed in this report.

5.1 Concept-Based Recommendations for the EOC of the Future

Each of the concept-based recommendations found in Table 4 can be traced back to an EOC of the Future concept defined in Section 3.3. For additional context regarding the background or need for these recommendations, please refer to the section identified in the Emphasis Area component. Concept-based recommendations incorporate insights from the TTXs as well. Additional recommendations that go beyond the EOC of the Future concepts discussed in this report can be found in Section 5.2.

[1] Barr, J., Hagen, A., Tietje, G., Betzsold, N., Greer, A., Best, E. (2024). “Emergency Management of Tomorrow Research – Artificial Intelligence Landscape Assessment.” Pacific Northwest National Laboratory.

Table 4. Concept-based Recommendations for the EOC of the Future

Emphasis Area	Value Adds	Enabling Tools
Build a solid data architecture foundation. (See 3.3.1)	• Enable continuous, real-time data collection. • Support interoperable technologies and systems. • Contextualize data and prevent corruption from misinformation and disinformation by collecting metadata such as origination/source, target audience, and purpose. • Create data pipelines that run horizontally (functional organizations) and vertically (jurisdictional agencies). • Create data sharing agreements that respect data privacy, support classified information, and sustain "need to know." • Fuse traditionally siloed, jurisdictional data that come with varying policies, privacy, and overall structure.	• Cloud architecture • Data fabric/mesh • Synthetic data • AI embedding for alternative data streams • IT infrastructure for AI
Promote continuous awareness and operations. (See 3.3.2)	• Enable information sharing across EOC functions, available in a variety of formats, and accessible on a variety of platforms. • Build situational awareness during normal, steady-state operations that can quickly transfer into an emergency. • Eliminate out-of-date situational awareness reports. • Enable real-time algorithm tuning and dashboard updates. • Improve the incident action plan process to support planners with the ability to almost instantly consider a range of future operational objectives and associated outcomes. • Facilitate enhanced public-private partnerships.	• Cloud, fog, and edge computing • IoT devices/sensors • AI-enabled productivity applications • Public-facing AI communication • AI-filtered domain awareness • AI-enabled planning • AI-enabled disaster prediction and detection • Risk models for optimal asset deployment • Modern optimization for asset deployment
Develop AI to become an EOC digital teammate. (See 3.3.3)	• Automate and enhance routine functions. • Leverage AI to deconflict response plans and aggregate after-action reports into a cohesive story.	• Robotics • Digital twins • See AI Research Landscape Assessment report[1] for

[1] Barr, J., Hagen, A., Tietje, G., Betzsold, N., Greer, A., Best, E. (2024). "Emergency Management of Tomorrow Research – Artificial Intelligence Landscape Assessment." Pacific Northwest National Laboratory.

Emphasis Area	Value Adds	Enabling Tools
	• Improve the capacity of the EOC, both in terms of speed and scale, filling gaps in human performance. • Enable sustained operations for long events and simultaneous events. • Empower human EOC personnel to perform more meaningful tasks. • Automate decisions with clear validation paper trails.	descriptions of highlighted and enabling technologies
Meet the needs of the individual operator. (See 3.3.4)	• Filter information and tailor its sharing to the needs, job functions, preferences, and abilities of the end user. • Tailor messages not only for understanding (i.e., language translation) but consumption and responsive action as well. • Optimize the accessibility and functionality of vast quantities of data, information, and intelligence.	• Human factors research • Augmented and virtual reality • Digital twins • Dashboards • AI-enabled productivity applications • AI-filtered domain awareness
Leverage digital tools to transcend physical boundaries. (See 3.3.5)	• Exploit hybrid operations to reduce EOC activation and response times. • Eliminate staffing problems for short- and long-term incidents. • Meet the demands of individual emergencies through increased flexibility and scalability. • Support EOCs and personnel that may have asymmetric levels of virtual capabilities. • Create seamless coordination, collaboration, and communication regardless of where personnel are located.	• Advanced wireless communications • Cloud architecture • Virtual video/audio conferencing and collaboration tools • Autonomous platforms • IoT devices • IT infrastructure for AI
Adopt a layered approach to technology integration and EOC functionality. (See 3.3.6)	• Develop information security plans with buy-in from all data and information sharing stakeholders. • Provide context (confidence) for key decision or capability metrics. • Validate data input and AI output recommendations and decisions. • Mitigate single-point-of-failure risks through decentralization, redundancy, scalability, and democratization of functions.	• Cloud architecture • Cybersecurity best practices • Security of AI assets and data • Modeling, simulation, and digital twins • IT infrastructure for AI • Governance and public perception of AI

Emphasis Area	Value Adds	Enabling Tools
	• Maintain institutional knowledge and core EOC capabilities as functions within the EOC are lost during an incident.	
Crowdsource EM information gathering and response capabilities. (See 3.3.7)	• Enable a wider range of players to participate in incident management. • Foster diversity in approaches to EM, benefiting policy development, information exchange, and shared situational awareness. • Leverage data, information, intelligence, and personnel beyond traditional sources, prioritizing public-private partnerships. • Achieve community buy-in toward support and progress for EM.	• IoT devices • Social media data analytics • Data fabric/mesh • Situational awareness tools • Public-facing AI communication • AI-filtered domain awareness • AI-enabled disaster prediction and detection • AI-enabled recovery and prediction • Risk models for optimal asset deployment • Governance and public perception of AI
Attract, train, and retain emergency managers of the future. (See 3.3.8)	• Build new relationships and strengthen existing relationships to increase community engagement. • Create a new generation of EM roles and responsibilities while maintaining current critical institutional knowledge. • Extend EM training to volunteers for just-in-time incident circumstances by streamlining background checks and putting systems in place to leverage a diverse set of skills.	• Augmented/virtual reality • Public-facing AI communication • AI-enabled planning • AI-enabled disaster prediction and recovery • AI-enabled recovery and prediction • Risk models for optimal asset deployment • Modern optimization for asset deployment

5.2 Supplemental Recommendations for the EOC of the Future

Leveraging PNNL's subject matter expertise pertaining to first responders and EM as well as work performed at PNNL on behalf of other sponsors, supplemental recommendations are provided in Table 5. These are not directly linked to a single EOC of the Future concept; however, they further support EMOTR findings and analysis.

Table 5. Supplemental Recommendations for the EOC of the Future

Emphasis Area	Value Adds	Enabling Tools
Exchange lessons learned with other federal agencies in developing open architecture.[1,2]	• Establish a set of open, commonly available, and standardized data interfaces, exchanges, and formats that enable a plug-and-play system similar to third-party applications developed for smartphones. • Support interoperability and a vendor-agnostic design of data management systems. • Allow third-party vendors to develop and easily implement proprietary capabilities on field-deployable technology.	• Cloud architecture • Data fabric/mesh
Assess potential cascading impacts of EOC of the Future realization.	• Identify new or modified EOC positions and functions that will be created as technology becomes increasingly more integrated. • Prevent unintended consequences from increased reliance on technology, such as the loss of root-cause understanding of emergency events. • Participate in policy discussions across the federal government regarding AI implementation.	• Organizational psychology • Human factors • Social science
Stand up an EM-focused innovation testbed.	• Create a living laboratory to get emerging tools and technologies into an EOC and into the hands of EM personnel. • Demonstrate, test, and even break emerging tools and technologies in an operational environment.	• Operational field assessments • Systems engineering • Red teaming • Rapid deployment
Develop an AI-Ready Workforce curriculum.	• Establish AI literacy standards for a variety of roles for EM personnel, particularly those who will use, interact with, and evaluate AI. • Define AI roles and develop training, processes, and technologies to support each role. • Orchestrate the successful integration of AI into EOC workflows, consolidate tasks, and build trust in AI among EM personnel.	• AI assurance • AI explainability • Human factors

[1] Cox, A. E. 2016. "OTAP Overview 04112016." Conference: Proposed for presentation at the Non-Destructive Inspection held May 11-12, 2016 in ABQ, NM, US., United States. https://www.osti.gov/biblio/1375606
[2] Stratovan. 2023. OPSL – Collaboration Between Application and Capability. https://www.stratovan.com/products/open-platform-software-library-opsl

Emphasis Area	Value Adds	Enabling Tools
Create and engage with spaces for students and early-career professionals.	• Engage with generations growing up with AI and emerging technology, who understand how these can be applied in a variety of settings, including EM. • Develop a robust talent pipeline that is well-positioned for the transition to the EOC of the Future.	• Sandpit activities[1] • Augmented/virtual reality trainings • Degree and certification programs and courses

5.3 Considerations

The EOC of the Future recommendations reflect potential opportunities to respond to high-level areas of EM R&D need and opportunity to benefit the future of EM and EOCs. Opportunities vary greatly by time and level of effort required for implementation—some are longer or shorter term recommendations that can be achieved, some will require significant R&D investment to achieve in the longer term, and some can be enabled by federal government development and ownership (i.e., public safety network). Each recommendation, gap, or opportunity will benefit from further exploration to roadmap the feasibility, timing, barriers, and needs for implementation. Furthermore, testbeds, operational field assessments, and pilot programs partnering government, academic institutions, and industry with the EM community can test emerging technologies and capabilities in real time and with real-world scenarios to deliver solutions that fit end-user needs. Additionally, visioning exercises with academic partners and other venues tailored to young and early-career professionals can engage the next generation in out-of-the-box thinking to envision how the aforementioned recommendations and other emerging technologies can benefit EM.

6.0 Conclusion

The EM threat landscape is evolving at an unprecedented pace—and so is the technology that EOCs can use to address it. This report explored the evolution of EOCs and technology, in conjunction with prior EMOTR findings (landscape assessments, stakeholder inputs, etc.), to highlight how a next-generation EOC requires dynamic and adaptable approaches that leverage new technologies and integrate existing R&D with EM capabilities. Through a structured literature review, use cases, and TTXs, PNNL sought to validate EMOTR findings with hands-on activities exploring where AI might benefit EM operations and EOCs of the future.

By combining previous EMOTR findings with a basic understanding of other operations center domains, foundational concepts for the EOC of the Future emerged, focused on data management, communication, human-machine teaming, physical EOC spaces and systems, and workforce development. PNNL further explored the EOC of the Future concepts through use cases and TTXs, utilizing operational stakeholders to evaluate the potential impacts of emerging technologies on EM operations. This report summarized all of these inputs, outputs, and exercises into a series of recommendations for a next-generation EOC to inform future research, development, and investment.

[1] Barr, J., Hagen, A., Tietje, G., Betzsold, N., Greer, A., Best, E. (2024). “Emergency Management of Tomorrow Research – Artificial Intelligence Landscape Assessment.” Pacific Northwest National Laboratory.

Recommendations for the EOC of the Future designed to assist DHS S&T in future decision-making and investment are outlined in Table 6 (and explored in detail in Table 4 and Table 5).

Table 6. EOC of the Future Recommendations

Concept-Based Recommendations	Supplemental Recommendations
• Build a solid data architecture foundation. • Promote continuous awareness and operations. • Develop AI to become a digital EOC teammate. • Meet the needs of the individual operator. • Leverage digital tools to transcend physical boundaries. • Adopt a layered approach to technology integration and EOC functionality. • Crowdsource EM information gathering and response capabilities. • Attract, train, and retain emergency managers of the future.	• Exchange lessons learned with other federal agencies in developing open architecture. • Assess potential cascading impacts of EOC of the Future realization. • Stand up an EM-focused innovation testbed. • Develop an AI-Ready Workforce curriculum. • Create and engage with spaces for students and early-career professionals.

To advance these high-priority building blocks for the EOC of the Future, more work is needed to create a plan for how these recommendations can come together in the real world (a space commonly bound by policy, procedural, and funding barriers). Potential near-term opportunities for achieving these concepts include:

- Defining open architecture standards and best practices as a reference guide for local jurisdictions to begin laying the groundwork for data and information sharing.
- Developing operationally secure requirements for deploying AI-enabled productivity applications (e.g., converting situation reports to slides/videos, deconflicting situational awareness information) in EOCs.
- Creating AI and other emerging technology training modules and certifications for EM.
- Engaging more frequently and intentionally with students and early-career professionals on careers in EM and EOCs of the Future.

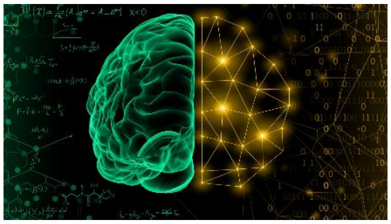
Prioritizing the concepts, recommendations, and opportunities outlined in this report can benefit the future of EM and EOCs, including:

- Increased data and information sharing
- More effective and up-to-date situational awareness
- EOC personnel free to focus on more meaningful tasks
- Increased flexibility and scalability (reduced staffing and resource challenges)
- Greater participation and diversity of participants in incident management.

Appendix A – EOC of the Future Technologies

The list of technologies in this section is not exhaustive. Rather, it is a list of technologies with notable application to the EOC of the Future concepts defined in section 4.0.

A.1 Artificial Intelligence



AI generally includes technology and machines exhibiting human intelligence (e.g., visual perception, speech recognition, decision-making). A growing body of research exists on AI assurance—assessing the trustworthiness of AI systems—and explainable AI—describing AI system impacts and biases. Generative AI (e.g., ChatGPT[1]) creates or generates new content in response to prompts. This capability includes capabilities ranging from text analysis to intelligent virtual assistants to image and video creation[2] to robotics.[3] Predictive modeling is a class of analytical tools within AI. In EM, AI currently can be used to write emails, develop briefing slides, handle 9-1-1 calls, and more.

A.2 Internet-of-Things Devices

IoT devices are everyday devices that can transmit/receive a signal/data (e.g., Wi-Fi, Bluetooth, wireless network). Often called "smart" devices, these can include wearables such as watches, earbuds, shoes, and rings, to more complicated systems such as cars and homes. For example, PNNL developed the VitalTag technology—a wearable health monitor that wirelessly transmits a patient's vital signs—to keep first responders connected to their patients in a mass casualty incident.[4]

A.3 Cloud, Fog, and Edge Computing

The old computing model generally involved physically collecting all the required data (e.g., spreadsheet, database), running algorithms (which could take considerable time), and then publishing the results. This model has evolved to be achieved virtually, directly on data collection devices, or both. Cloud technologies enable access to immense volumes of data coupled with high-performance computing. Enhanced processors and memory drives allow data storage and computing to be done closer to users and devices, without the cloud connection requirements. Fog computing enables short-term analytics at the edge, while the cloud performs resource-intensive, longer-term analytics. AI can help optimize which processes are done by each service. In EM, these capabilities overcome connectivity and efficiency challenges, such as during extreme weather and prolonged power or communication outages.

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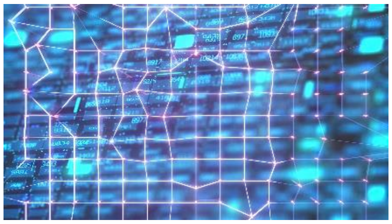
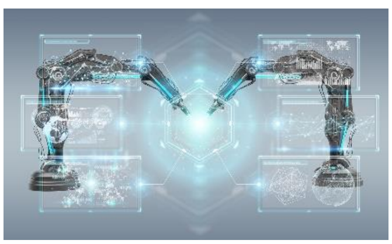
[1] https://chat.openai.com/
[2] https://openai.com/sora
[3] https://www.youtube.com/watch?v=Sq1QZB5baNw
[4] https://www.pnnl.gov/sites/default/files/media/file/DDST_0066_FLIER_AISummit_VitalTag_Web.pdf

A.4 Data Fabric and Data Mesh



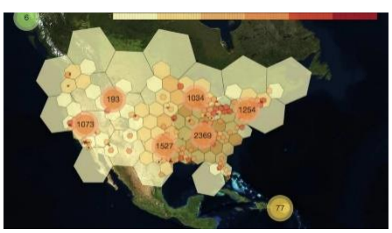
Particularly relevant to the next-generation data management concept (see section 3.3.1), data fabric and data mesh capabilities facilitate data fusion in the cloud and on-premises. Data fabric facilitates efficient identification of needed data inputs and construction of data pipelines to create necessary products from pooled data. Data mesh maintains distinct data sources aligned by function but still efficiently manages the associated (and sometimes differing) rules and regulations for the common greater good. A data fabric in EM could manage a centralized EOC repository containing 9-1-1 call audio, gunshot detection system data, EM personnel geolocation, and more to efficiently fuse these disparate pieces of information into an algorithm that can help optimize EOC resource allocation to an active shooter event. In comparison, a data mesh could allow various EOC components—police, fire, transportation, public information, etc.—to maintain their data repositories while providing application programming interfaces for the EOC at large to feed a broader situational awareness capability.

A.5 Robotics and Autonomy



Though fairly straightforward, in the context of EM this topic focuses on supporting tasks and functions that are not well suited for humans. This may be the result of understaffed EOCs, super-human levels of required precision, performing monotonous and prolonged tasks subject to fatigue, or hazardous environmental conditions. Robotics and autonomy can also help reduce the costs of job turnover and the loss of institutional knowledge for complex operations.

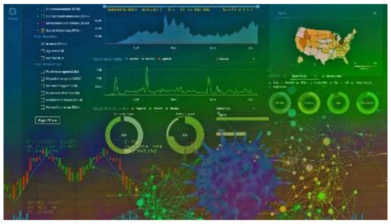
A.6 Situational Awareness Tools: Digital Twins and Geospatial Analytics



A variety of situational awareness tools exist and many have been integrated into EOCs (and EM in general) for quite some time. One example is the Rapid Analytics for Disaster Response tool developed by PNNL to deliver high-resolution, high-cadence, large-extent situational awareness for incident command and disaster management teams to understand hazard extent, communities affected, impacts to critical infrastructure, blocked transportation routes, structural damage, and safe locations to establish relief efforts.[1] Digital twins seek to recreate the physical world in a virtual environment, where the real power is in the amount of detail that can be integrated into simulations to develop optimal strategies. Geospatial analytics (e.g., GIS) factor in elements of space and time, enabling the identification of new patterns related to distance/proximity, density in a region, and shifts over time.

[1] https://www.pnnl.gov/projects/rapid-analytics-disaster-response

A.7 Social Media Analytics



Social media represents a public information source with vast amounts of data, which can be accessed without violating privacy. These data are a great early indicator of events, such as posts about people getting sick leading up to an outbreak. Conversations can be tracked and media campaigns can be measured to assess messaging effectiveness and reach. Moreover, a study has shown how social media data could have been used to construct a flood probability map using multiple posted images and videos with locations.[1]

A.8 Advanced Wireless Communications

Prior generations of wireless communications (3G/4G) focused on providing data to humans (e.g., the first smartphones). The current generation (5G) focuses on providing communications between humans and machines (e.g., IoT devices, edge computing). The next generation (6G) is still being defined but will follow a similar manifesto: higher data speeds, lower latency, more reliability, higher network capacity, and increased availability. Satellite communications such as Starlink can be included in this topic.[2] Communications technologies will be a critical component of the EOC of the Future.

A.9 Augmented and Virtual Reality

Augmented reality is designed to superimpose digital elements onto the real world. Virtual reality is an immersive experience that isolates users from the real world. This technology is rapidly advancing in the entertainment industry, such as Pokémon Go[3] and the Meta Quest 3.[4] Perhaps the best application of augmented and virtual reality in EM will be in improved training courses, keeping personnel familiar with their response plans and the tools they need during emergencies, regardless of how infrequent emergencies occur.[5]

[1] Eilander, D., P. Trambauer, J. Wagemaker, and A. Van Loenen. 2016. "Harvesting Social Media for Generation of near Real-Time Flood Maps." Procedia Engineering. https://doi.org/10.1016/j.proeng.2016.07.441
[2] https://www.starlink.com/
[3] https://pokemongolive.com/?hl=en
[4] https://www.meta.com/quest/quest-3/
[5] https://www.govtech.com/products/augmented-virtual-realties-hold-promise-for-government

Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354

1-888-375-PNNL (7665)

www.pnnl.gov