SAND2021-9528C

Prioritization of Emerging Technologies as Impacting the Field of International Nuclear Safeguards

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Abstract

Rapid technological advancement is bringing profound changes to many industries and will cause significant effects on the domain of international nuclear safeguards. Nuclear operators and safeguards stakeholders are already investing significant resources to address some of these new emerging opportunities and challenges. However, most of these efforts are done ad hoc, in many cases driven by intuitive perception of certain technologies. Systematic understanding of this massive technological evolution is of vital importance to identify both vulnerabilities and opportunities to increase the effectiveness and efficiency of safeguards, as well as to prioritize investment areas towards the development of safeguards technologies and approaches. This work was designed to provide a systematic assessment of a wide variety of technological concepts and specific applications, including analysis of the potential opportunities for and challenges to nuclear safeguards. The analysis framework was developed with the capability of handling a large number of technologies and the flexibility of being easily updated to accommodate the never-ending changes and rapid advancements in emerging technologies. This paper describes the analysis framework that was developed to perform a systematic assessment of a large number of emerging technologies. The technologies are then prioritized with regards to their impact on the field of international safeguards. Several examples of analysis process are also shown. *SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525. SAND2021-2743 A.*

Introduction

Rapid technological advancement will have significant effects on all peaceful nuclear applications and related fields, including the domain of international nuclear safeguards. A systematic understanding of this massive technological evolution is of vital importance for identifying potential opportunities to increase effectiveness and prioritize investment areas towards the development of novel safeguards technologies and approaches. In addition, identifying potential vulnerabilities introduced with such technologies is just as important. Multiple studies exist investigating the potential effects of individual or several emerging technologies on the nuclear safeguards sectors, but to date there have not been any publications on a holistic systematic assessment and prioritization of the specific impact of technological advancements on nuclear safeguards. In general, most of the efforts and discussions related to emerging technologies tend to focus on a specific technology or its application to international safeguards. Although such targeted investigations into individual emerging technologies may yield valuable results, these outcomes, or implementation ideas, are usually specific to certain scenarios. This approach tends to also not consider the benefits of implementing one technology relative to another. To complement other work in area, a systematic assessment of the relative impact of a wide variety of technologies and applications is important. This study aims to fill this gap by using a framework developed for prioritization of emerging technologies for

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nuclear security and applying it to the field of international safeguards [1]. The implementation of this framework resulted in a systematic assessment of a wide variety of technological concepts and specific applications for the field of nuclear safeguards. These effects were assessed from both perspectives of identifying opportunities for strengthening international nuclear safeguards as well as identifying potential challenges to the international safeguards regime.

Definitions of Emerging Technologies

The objective of this study was to conduct a systematic assessment of a wide spectrum of *emerging* technologies. Hence, defining the term 'emerging technology' is important to effectively select technologies for this analysis. A number of definitions are used in the literature to describe novel technologies that are currently in conceptual and developmental stages. However, for the purposes of this study, the following definition was used:

> *Emerging technologies* are technical innovations that breach new territory in a particular field or area of human life. These are innovative technologies that open up new avenues for market and lifestyle transformation. Some of the emerging technologies are developed via theoretical research, while others are based on commercial research and development.

This definition is broad and includes a wide spectrum of technological advances. It was also observed that most of the novel technological applications being developed and introduced to the market use multiple technological concepts in their design. In addition to defining emerging technologies, we make the distinction between *technological concepts* and *technological applications*. In this study, broad *technological concepts*, such as artificial intelligence (AI), are used to serve as high level categories for specific technological areas. *Technological applications*, as defined in this study, are specific technologies or tools created for a particular task using the emerging technological concepts. An example of a technological application would be enhanced radiation detection algorithms using AI. Technologies were then selected based on the following inclusion criteria:

- technology that has been developed or proven feasible recently (some of the emerging technologies have been discussed conceptually for a while, but only recently became a reality), or
- technology that has not been broadly implemented into safeguards applications (certain technologies that have entered the consumer market or which are implemented in other industries could still be considered emerging from a safeguards standpoint), or
- technology that has a path for development over the next 5 - 10 years

The scope of this work was further restricted by excluding emerging nuclear fuel cycle technologies, such as advanced reactors or novel uranium enrichment techniques, from this analysis. Emerging nuclear technologies and their impact on international safeguards are considered under current safeguards-by-design, safeguardability, and proliferation resistance research in other projects. The purpose of this study was to identify emerging technologies outside of the direct nuclear fuel cycle scope and their potential impacts to nuclear safeguards.

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Emerging Technologies Analysis Approach

Analysis Framework

An effective analysis framework capable of compiling a large number of technologies, assessing their impact on the nuclear safeguards mission, and prioritizing them was needed for this study. An analysis framework for evaluating emerging technologies for nuclear and radiological security applications was developed by Sandia National Laboratories in 2019 [1] which was adapted for the international safeguards analysis task with a number of modifications. In order to achieve the objectives of the study, the analytical framework had to fulfill a number of requirements:

- effectively address specific safeguards mission areas
- be flexible (capable of adding and removing technologies to the analysis)
- be scalable (capable of handling a large number of technologies and applications)

The analytical framework was developed as a matrix with technologies and their applications along the vertical axis and criteria describing the safeguards mission areas on the horizontal axis. The criteria describing the safeguards mission areas were split into two general categories: one for the capability to strengthen the safeguards regime (based on *strengthen* criteria) and one for the capability to challenge safeguards (based on *challenge* criteria). The cells of the matrix contained specific scenarios showing potential uses of the technologies within the corresponding safeguards criteria along with assigned scores. Scenarios were developed using subject matter expert (SME) input, considering the intersection of the technology for application within the specific safeguards mission space. This structure allowed for the analysis of technologies against various criteria and the grading of each technology's contribution to various functional areas within the safeguards mission space. The full schematics of the analysis structure are shown in Fig. 1. Once completed all scenarios were graded using the risk matrices described later in this section (see Risk Matrices paragraph). For technologies that have more than one scenario in a particular criterion, the highest-scored scenario was used for calculating the final technology score.

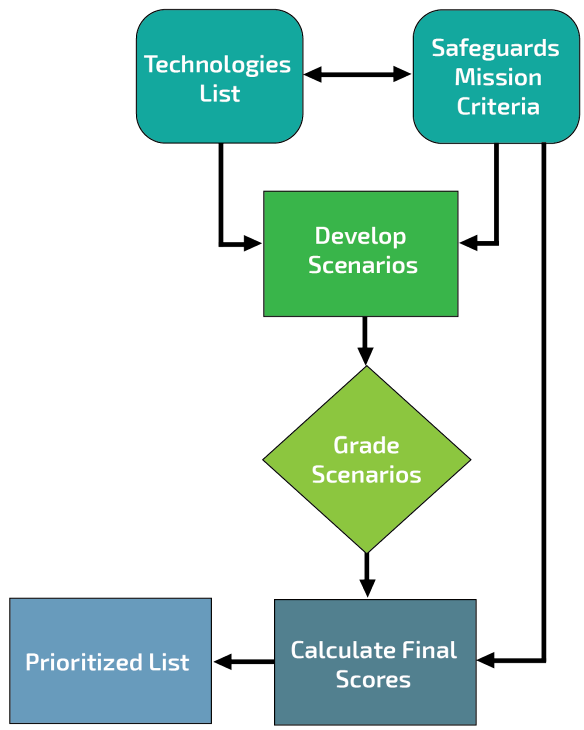

Figure 1: Analysis Framework Flowchart

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Safeguards Mission Criteria

To address the safeguards mission space and capture all important elements of the international nuclear safeguards system, a unique set of criteria was developed. The criteria employed by the analysis framework in this study provided a comprehensive description of the main elements of the safeguards regime. Two separate categories were considered: *strengthen* and *challenge*. The *strengthen* category addresses potential new opportunities that emerging technologies may present to enhance the performance of the international safeguards regime. For example, detection of undeclared material or the diversion of declared material are some of the criteria that fall within this category. The *challenge* category addresses the ways in which new technologies can be used to challenge or create threats to the safeguards system, such as the misuse of facilities or the interference with the International Atomic Energy Agency's (IAEA) activities.

Risk Matrices

In order to quantify a specific scenario's impact and develop a numerical evaluation of the technologies and applications, two risk matrices were used. One matrix for each the *strengthen* impact, and the *challenge* impact. Their purpose was to allow SMEs to *quantitatively* grade the *qualitative* likelihood of a particular scenario taking place in the future, and its impact on the safeguards mission space. Each matrix had four degrees of likelihood ranging from 'improbable' to 'highly probable.' Impact had four degrees of consequences ranging from 'acceptable' to 'intolerable' for *challenge* and from 'trivial' to 'critical' for *strengthen*. Once the likelihood and impact were assessed, a score from the matrix was assigned to each scenario. The risk matrices used in this study are shown in Fig. 2.

Strengthen

	IMPACT			
	TRIVIAL LITTLE TO NO EFFECT	MINOR EFFECTS ARE FELT, BUT NOT CRITICAL TO THE MISSION	MAJOR SERIOUS IMPACT ON THE MISSION	CRITICAL COULD RESULT IN A COMPLETE CHANGE OF APPROACH
LIKELIHOOD				
IMPROBABLE UNLIKELY TO OCCUR	VERY LOW – 1 –	LOW – 2 –	MEDIUM – 6 –	HIGH – 9 –
POSSIBLE MAY OCCUR	LOW – 2 –	MEDIUM – 5 –	HIGH – 8 –	VERY HIGH – 10 –
PROBABLE WILL MOST LIKELY OCCUR	MEDIUM – 6 –	HIGH – 8–	VERY HIGH – 9 –	EXTREME – 11 –
HIGHLY PROBABLE WILL DEFINITELY OCCUR	HIGH – 8 –	VERY HIGH – 10 –	EXTREME – 11 –	EXTREME – 12 –

Challenge

	IMPACT			
	ACCEPTABLE LITTLE TO NO EFFECT ON THE SYSTEM	TOLERABLE EFFECTS ARE FELT, BUT NOT CRITICAL	UNDESIRABLE SERIOUS IMPACT TO THE SYSTEM MISSION	INTOLERABLE COULD RESULT IN DISASTER
LIKELIHOOD				
IMPROBABLE UNLIKELY TO OCCUR	VERY LOW – 1 –	LOW – 2 –	MEDIUM – 6 –	HIGH – 9 –
POSSIBLE MAY OCCUR	LOW – 2 –	MEDIUM – 5 –	HIGH – 8 –	VERY HIGH – 10 –
PROBABLE WILL MOST LIKELY OCCUR	MEDIUM – 6 –	HIGH – 8 –	VERY HIGH – 9 –	EXTREME – 11 –
HIGHLY PROBABLE WILL DEFINITELY OCCUR	HIGH – 8 –	VERY HIGH – 10 –	EXTREME – 11 –	EXTREME – 12 –

Figure 2: Risk Matrix for Safeguards *Strengthen* and *Challenges* Analysis [5]

Final Score Calculation

Once the scenarios were complete and graded, final technology scores were calculated by averaging the scores of all scenario developed for that technology. It is noted that all criteria within a category were equally weighted, hence, the average score of all scenarios within a category was calculated as follows:

$$TS_i = \frac{1}{N}\sum_{j=1}^{N} S_j, \tag{1}$$

where:

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- TS_i: is technology i score. Either be the strengthen score (TSS_i) or challenge score (TCS_i)
- S_j: is scenario j score
- N: is the total number of criteria

The final technology *strengthen* and *challenge* scores were used to produce a prioritized list of technologies.

Technology Prioritization

The last step of the analysis was assembling the final prioritized list of technologies and applications. Considering that the analysis was based on two categories of criteria, *strengthen* and *challenge*, the final results were presented in a form a two-dimensional plot. The *strengthen* score was plotted along the horizontal axis while *challenge* score was plotted along the vertical axis. Such graphic allowed for the observance of a potential 'net' effect, considering both positive and negative, that the assessed technologies may have on international safeguards.

Sample Analysis

What follows is a short demonstration of applying this framework to an analysis of emerging technologies as they impact international safeguards. This sample is only intended to show how the analysis works and the results are not intended to be used in any type of decision-making.

List of Technologies

Three technological concepts were considered to demonstrate the analysis process and outcomes. Within these technological concepts five specific applications were selected as outlined and defined in Table 1.

Analysis Criteria

Following the selection of technologies, the next step was to specify the analysis criteria. Again, for the simplicity of demonstration, a total of four criteria were chosen. Two from the *strengthen* and the other two being from the *challenges* category with all criteria within a given category were assigned equal weights. The full list of criteria considered in this sample analysis along with the elements encompassed within each one are shown in Table 2.

Scenarios and Analysis

The next step was the development of scenarios for each technology-criteria pair and grading these scenarios using the risk matrices shown in Figure 2. For a large number of technologies and criteria it may be extremely labour intensive to develop detailed intricate scenarios; therefore, the approach suggested is to create brief but meaningful scenarios for each technology-criteria pair. Examples of scenarios for the technologies and criteria used are:

1. *Low-Volume Production*: The production of spare parts at facilities or regional offices for faster repairs and maintenance of critical equipment

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Table 1: List of technologies used in sample analysis

Technology Application	**Definition**
Additive Manufacturing	Commonly referred to as 3D printing, it is the process of joining materials to make objects from 3D model data.
Low-volume production	Capability to produce unique and complex design items or parts in single items, no production line needed.
Counterfeit goods production	Goods or components designed and produced to mimic a trusted product from a trusted supplier; products can range from counterfeit consumer goods, to credit card scanners, and even include false parts for military hardware [3]
Autonomy	The capability of machines to operate and perform tasks independently without explicit human control [4]
Autonomous Vehicles	A vehicle which can accomplish its goals of maneuvering to a destination with minimal supervision from human operators in environments that are complex and unpredictable. Has software allowing it to make decisions without human operator input
Information and Data Analysis	The process of examining data sets in order to draw conclusions about the information they contain, increasingly with the aid of specialized systems and software. [6]
Crowd sourcing	Using a large set of individuals to perform tasks too time-consuming for a small group
Video/Photo Analytics	The use of computer algorithms to translate a recorded video into a useful data insight, which, in turn, aids in business or operation. It is real time, granular, authenticated. [2]

Table 2: List of criteria used in sample analysis

Criteria	**Encompassed Elements / Definition**
	Strengthen
Detection of Diversion of Declared Material (DM)	Nuclear Material Accountancy, Physical Measurements, Remote/Unattended Monitoring, Containment and Surveillance
Detection of Undeclared Material (UM)	Nuclear Material Accountancy (NMA), Physical Measurements, Environmental Sampling
	Challenges
Facility Misuse (FM)	The use of facilities under safeguards in addition to, or outside of, declared use to the IAEA
IAEA Activities Interference (AI)	Malicious interference with IAEA verification activities with an intent of concealing diversion, facility misuse and any other undeclared activities or facilities.

2. *Counterfeit Goods Production*: Creation of a material container or facility modification with hidden compartments to conceal material or equipment

3. *Autonomous Vehicles*: The use of fully autonomous vehicles in inspection activities to aid inspectors, access hazardous areas and perform long mundane tasks

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4. *Crowdsourcing*: Infiltration of these activities by states/operators to distract IAEA attention from the right areas
5. *Video/Photo Analytics*: Analysis of imagery data from a nuclear facility to identify anomalous activities which may indicate diversion

To demonstrate the approach used to score developed scenarios, scenarios 2 and 5 were selected for grading. Using the risk matrices shown in Figure 2, the likelihood and potential consequences of these scenarios were evaluated. For scenario 2, the likelihood of technological development for additive manufacturing to reach the level that would enable adversaries to produce material containers or facility modification with hidden compartments to conceal material or equipment was selected as “possible”. Nevertheless, the impact of such application would have “undesirable” consequences. Therefore, based on the *challenge* risk matrix the overall score for this scenario was 8. As for scenario 5, the likelihood of being able to apply Video/Photo analytics towards the analysis of imagery data from a nuclear facility to identify anomalous activities which may indicate diversion was considered “probable”. The impact of such application, on the other hand, would have a “major” impact; therefore, a score of 9 was assigned to this scenario using the *strengthen* risk matrix. The remainder of the developed scenarios were graded in a similar fashion. Table 3 shows the final scores of the developed scenarios along with the calculated totals for both the *strengthen* and *challenge* criteria.

Table 3: Sample analysis scoring

Technology Application	**Criteria**					
	Strengthen			**Challenge**		
	DM	UM	**Total**	FM	AI	**Total**
Additive Manufacturing						
Low-volume production	8	8	**8**	10	0	**5**
Counterfeit goods production	0	0	**0**	8	8	**8**
Autonomy						
Autonomous Vehicles	8	8	**8**	5	0	**2.5**
Information and Data Analysis						
Crowd sourcing	0	0	**0**	0	5	**2.5**
Video/Photo Analytics	9	9	**9**	0	0	**0**

Final Results

Once the final scores were calculated, the results were plotted on a two-dimensional plot as shown in Figure 3. From the graph, the relative impact of technologies on both the *strengthen* and *challenge* criteria is assessed and a prioritized list of technologies is created

Conclusions

Over the next several years and decades, emerging technologies can have a profound impact on the field of international safeguards by providing opportunities for enhanced operations and performance, and also by creating new challenges. Acknowledging the importance of having a thorough

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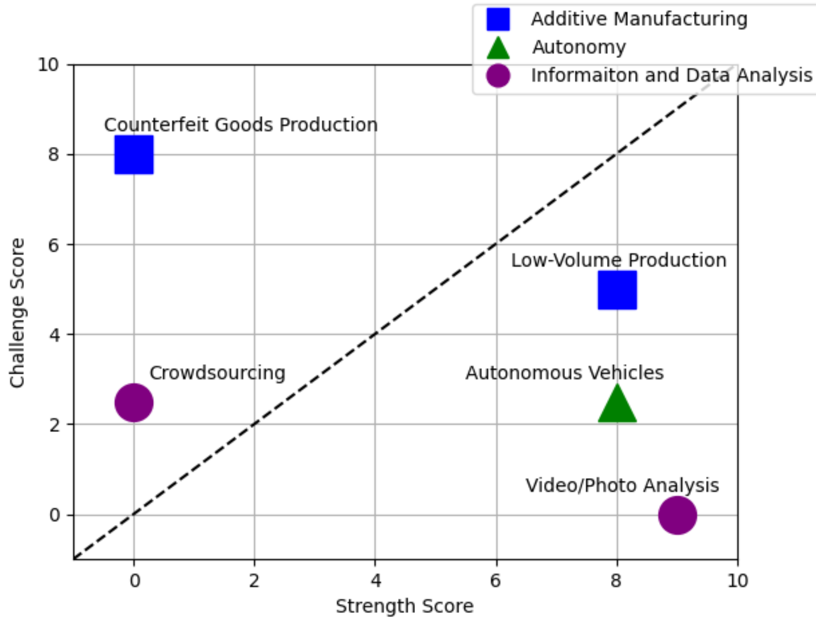

Figure 3: Sample Analysis Final Results Graph

understanding of the technological landscape, Sandia has developed an analysis methodology and conducted a prioritization study to assess the impacts that various technologies could have on the safeguards mission carried out by the IAEA. The analysis was performed in a series of steps, starting with a characterization of the nuclear safeguards mission through the development of an all-encompassing set of criteria, followed by assembling a list of technologies, and finally developing scenarios for each technology-criteria pair and grading these scenarios. The outcome of this work was a set of prioritized lists based on the potential opportunities for strengthening safeguards and on potential challenges that analyzed technologies may pose to the international nuclear safeguards mission.

This analysis framework, which was adapted from the framework developed for nuclear security analysis in 2019, allowed for the comparison of multiple technologies, their potential impacts, and prioritization through quantitative analysis. Inevitably, the process relied heavily on SME opinions, adding a degree of subjectivity to the results. The research team's approach to mitigating the effect of subjectivity was through close collaboration with a group of experts of diverse backgrounds, all of which have worked for the IAEA at some point of their careers.

In conclusion, there is a large number of novel technologies appearing. Despite their potential to advance the nuclear safeguards space, it is important to acknowledge the risks such technologies may introduce. In general, this analysis showed that there are more opportunities for new technologies to potentially support safeguards mission than risks being created. It is suggested that a periodic update to the safeguards emerging technologies study be conducted to align with the safeguards focus and priorities over time. Specifically, the roster of relevant emerging technologies that impact the safeguards mission space is likely to continue evolving and changing as the technologies themselves develop, or as new relevant technologies are added.

Acknowledgments

This work was funded by the U.S. Department of Energy National Nuclear Security Administration's Office of Nonproliferation and Arms Control, International Nuclear Safeguards program (NA-241), Concepts & Approaches portfolio. Authors would also like to thank NNSA 's Global Material Security program (NA-21) for supporting the initial emerging technologies analysis work that led to creation of analysis framework, which served as a foundation for this study.

References

[1] A.A. Solodov; et. al. *Emerging Technology Prioritization as Impacting the Office of Global Material Security.* Tech. rep. SAND2019-9158t. Sandia National Laboratories, 2019.

[2] R.N. Slaybaugh D.R. Farley M.G. Negus. *Industrial Internet-of-Things Data Analytics for Nuclear Power Safeguards.* Tech. rep. SAND2018-12807. Sandia National Laboratories, 2018.

[3] J. Greenbaum. *Illegal Immoral and Here to Stay: Counterfeiting and The 3D Printing Revolution.* https://www.wired.com/insights/2015/02/illegal-immoral-and-here-to-stay-counterfeiting-and-the-3d-printing-revolution/. Accessed: 2020-08-24.

[4] Andrew Ilachinski. *AI, Robots, and Swarms Issues, Questions, and Recommended Studies.* Tech. rep.

[5] A. Marker. *Risk Matrix Templates.* https://www.smartsheet.com/all-risk-assessment-matrix-templates-you-need. Accessed: 2020-06-12.

[6] M. Rouse. *Data Analytics, Definition.* https://searchdatamanagement.techtarget.com/definition/data-analytics. Accessed: 2020-08-24.

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