SAND2020-5899C

Application of System-of-Systems in Pulsed Power Research Operations

Andy Yu, Sandia National Laboratories

Abstract

Demands are growing on organizations that routinely study and perform novel experiments into nuclear fusion to increase capability and rate of scientific output with fewer resources and tighter budgets. This paper analyzes a large nuclear fusion research center, specifically the Z-Machine at Sandia National Labs, using two established System-of-Systems (SoS) frameworks. New systems at Z-Machine have been continually developed alongside legacy systems to maintain and advance capability. The subsequent system is comprised of varyingly coupled systems and pressures different than that of traditional ground-up monolithic systems. Results from applying SoS frameworks have informed analysis, impacted stakeholder decisions, and development of projects.

1. Introduction

Pulsed power experiments are routinely performed for scientific inquiry regarding fusion, fundamental sciences, radiation, and material properties. Facilities responsible for executing these experiments, or pulsed power facilities (PPFs), have strived to keep pace with demand through dynamic and incremental changes to equipment, processes, and organizations for the last 4 decades [1]. However, as the demand for new capabilities and rate of scientific output have increased, availability of resources required to produce those outcomes, including time and budget, are becoming further constrained [2] [3].

The confluence of system upgrades and modifications has resulted in a modern PPF that resembles a tightly coupled heterogenous system. This heterogenous system, developed over time through small and incremental changes exhibits both managerial and operational independence [4], i.e. the heterogenous systems can operate and manage independent of the PPF. Based on these characteristics, frameworks in the field of System-of-Systems (SoS) show promise in characterizing and analyzing PPFs for the purpose of improving resource management and operational capability [5].

SoS frameworks are unique in that they allow researchers and analysts to capture multiple levels of system properties and interactions without trivializing or simplifying the system beyond recognition. Moreover, SoS analysis techniques can be used to better inform stakeholders of emergent behaviors (i.e. latent properties in complex interactions and relationships that are not immediately known. Previous work has successfully applied SoS frameworks in a variety of industries to perform a similar analysis [6] [7] [8]. However, translating analysis outcomes into impactful, practical activities remains a challenge. The goal of this paper is to illustrate how to apply some existing theoretical SoS frameworks in complex pulsed power fusion research applications into feasible and actionable projects to improve operational efficiency and effectiveness.

2. Background

2.1. Pulsed Power Facilities: Z Machine

PPFs are responsible for executing complex experiments in the field of nuclear fusion. These facilities require immense resources to operate successfully. One such PPF is Sandia National Laboratories' Z Machine. Z Machine (hereby called "Z") is the world's largest electrical PPF. Z exists to create and measure, in the lab, environments created during nuclear weapon explosions. Z is also routinely used in support of US nuclear stockpile stewardship and scientific inquiry into fundamental sciences, radiation effects, dynamic materials properties, and inertial confinement fusion. The organizations developed to support Z experiments, over the past two to three decades, exhibit the properties and behaviors of a SoS [4] [9]

Since its creation in 1985, Z has gone through several upgrades and refurbishments [10] [11] [12] that have largely changed experiment configuration, execution, and supporting operations in major ways. New technological support systems, often custom and single purpose, have been continually developed and integrated alongside legacy systems to maintain and advance capability. These systems are often developed, relatively, faster than the supporting technological infrastructure. Organizations of subject matter experts (SMEs), engineers, and fielding teams are frequently created and used to address these gaps. The collection of such organizations has led to the evolution of many

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

traditions, attitudes, and beliefs with varyingly levels of managerial and operational independent commonly found in SoS.

2.2. Previous Approaches

A review of Z management approaches resulted in a wide range of methods from fields such as quality management, organizational management, and engineering. Many of these approaches assume complex systems can be broken down into measurable and predictable components (i.e., subsystems) then reconstructed with a collection of solutions [13]. These reductionist techniques applied to complex systems, like PPFs, have proven largely ineffective in identifying, communicating, and addressing tightly coupled challenges [14]. Previous attempts to use SoS has led to fundamental and routine challenges in discussions of the structure, behaviors, or goals at Z. The lack of common nomenclature for use by the varied PPF stakeholders and participants coupled with difficulty developing a lexicon to communicate ideas effectively at Z has been a challenging barrier [4]. To better address these gaps, work in SoS contextualization and taxonomy development is used as a starting point.

3. Method: Applying SoS in PPF

3.1. Z in Perspective of SoS Applications

The ability to study PPFs can prove problematic given the limited number of PPFs in the world, restricted access, and limited amounts of literature. Comparing Z to the broader SoS domain would expand the generalizability of PPFs and help identify potential avenues for additional SoS literature, methods, and frameworks most appropriate for analysis and design. DeLaurentis et al [6] proposed that SoS can be further contextualized to provide a qualitative comparison across multiple types of SoS domains. The comparison of dimensions occupied by various SoS lends itself to identifying the appropriate mix of entities and whether investments are needed to achieve them.

The qualitative construct proposed by DeLaurentis et al [6] offers three dimensions across which a system can be evaluated proposes using three dimensions: connectivity, autonomy, and topology (CAT). *Connectivity* is defined as the strength of the systems relationships captured on a spectrum between high and low connectivity. *Autonomy* represents the spectrum of control for a system between fully centralized and fully decentralized. The spectrum at which the SoS is comprised of technical and/or human systems is captured under *topology*. CAT has been used to analyze several SoS such as air transportation, healthcare, and yellow taxi cabs [6][8].

3.2. Shared Lexicon for Stakeholders

The development of a lexicon in PPFs to communicate effectively with the varied organizations and levels within each organization have been a challenging barrier. A SoS lexicon has been proposed to address the need for effective communication in multi-level and multi-domain SoS [15]. The lexicon uses a relational hierarchy across four perspectives to systematically represent SoS using an unambiguous lexicon and scope. Emphasis on the networks and the relationships of entities, imposed by the relational hierarchy, lends itself to understanding what investments need to be made to critical nodes.

The information is expressed as a table of resource, operation, policy, and economics (ROPE) for each relational hierarchy (expressed as α, β, γ, and δ). *Resources* are entities that are the physical manifestation of the system-of-system; *operations* are the application of policies/procedures to direct the activity of physical entities; *policies* are external forcing functions that impact physical and non-physical entities; and *economics* are the non-physical systems that provides a valuation of the operation of physical entities in a market economy.

The use of CAT and ROPE is applicable to contextualization and taxonomy development for Z and can be further generalized to PPFs. In order to collect a wide range of data related to the various aspects of Z operations, the author conducted observations and interviews with Z SMEs and management over a 3-month period. Relevant data were collected and used to develop a CAT and ROPE table about Z. Emphasis was placed on capturing perspectives that previous studies did not include (e.g. relationship of available resources to operations, policy to operations, economics of resources).

4. Results

4.1. CAT Diagram with PPF

Given the qualitative nature of each dimension in the CAT construct, the placement and spectrum of each SoS should be treated as an estimate rather than an exact value. Nevertheless, the CAT Diagram is still useful in understanding how PPFs compare to other SoS applications. Z was used as a representative case for PPF SoS and provide a means to perform a qualitative comparison between PPF and SoS across connectivity, autonomy, and topology dimensions.

Figure 1 presents the CAT diagram. The solid double-arrowed lines represent each dimension of CAT. Each SoS is represented as a box with dashed lines that represent the estimated spectrum along the given dimension. Vertical space in each dimension is used to provide more distinct separation between SoS that occupy similar spaces.

individually owned taxis that operate independent of one another. Each cab determines their route, hours, and if services are rendered. This is exceptionally different compared to a centralized SoS like air transportation where higher level governing bodies often dictate how, when, and where services are rendered.

Finally, PPF are comparable to healthcare in

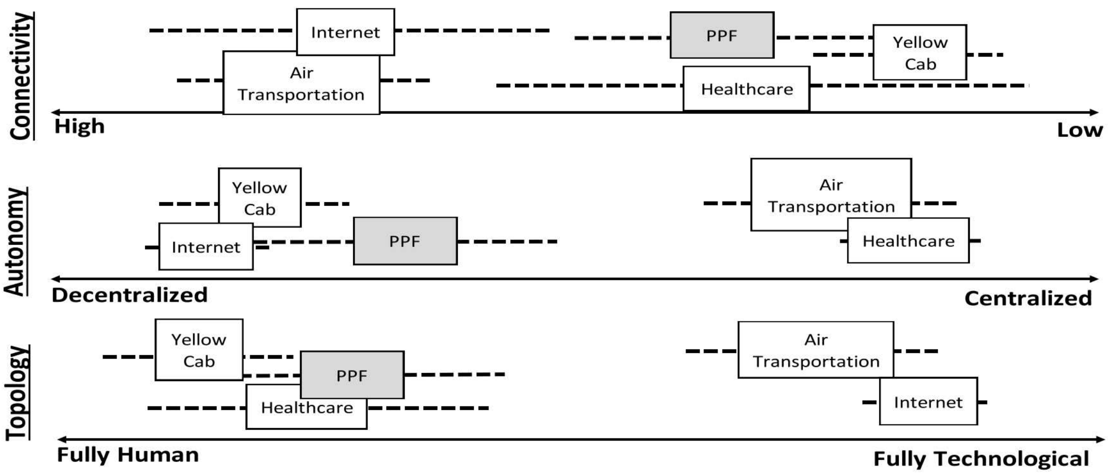

Figure 1: CAT Diagram with PPF (Z)

PPF facilities are more comparable in the connectivity dimension to healthcare than yellow cab (lower than PPF) and an even lesser extent to internet or air transportation (higher than PPF) SoS applications. This is consistent with the qualitative measure that PPFs are comprised of many varyingly coupled systems. Systems critical to the basic function of a given PPF are often tightly coupled, whereas other systems (often single purpose) are loosely coupled by temporary support structures. Similarly, healthcare facilities will often integrate specialization systems core to their service but be loosely connected by a shared element (e.g. insurance, patient, function, etc.). The connectivity difference is glaring when compared to air transportation SoSs that share many tightly coupled systems (e.g. runways, airports, regulating bodies, etc.) and heavily depend on the coordination of one another to prevent delays or accidents.

Within the autonomy dimensions, PPF are more centralized than the yellow cab and internet SoS, but significantly more decentralized compared to air transportation or healthcare SoS. The level of decentralization in a PPF is associated with the level of complexity needed to support the various systems. The ability to operate any given system in a PPF often requires the collaborative effort of multiple SMEs. This unique position has allowed these collaborative efforts to form organizations that operate independently of one another, seek their own funding, and determine investments. Similarly, yellow cabs consist of many

topology. PPF are less human based than yellow cab, but surprisingly and significantly less technological than air transportation or internet SoS. Despite the scientific and technological activities that define Z as an experiment facility, many systems depend on the use of humans (coordinators, SMEs, technicians, etc.) over automation or mechanization tools. Some activities require high precision or are considered high risk, which require personnel to perform them manually. This is akin to the use of nurses, doctors, and other specially trained medical personnel to perform many of the activities in a healthcare. Dissimilarly, the internet is an SoS that is primarily composed of many technological systems (e.g. server farms, IoT devices, etc.) and very few human systems, making it significantly more technological than a PPF SoS.

4.2. ROPE Table for PPF

The application of SoS frameworks captures multiple levels of system properties and interactions. An example of a ROPE table constructed for the Z-Machine is shown in Table 4. The author notes that his table provides a starting point for further evaluation rather than a comprehensive list of possible entities or networks. Marx banks are used as the primary example. PPF use marx banks to store electrical energy before releasing it. Quickly releasing the energy into the experiment creates a pulse of power capable of intense pressures used for fusion research.

charging marx banks to their upper limit and releasing all stored energy allows higher pressures to be reached but often results in the breakdown of several systems.

Very little has changed for α and β resources while respective operations and policy have evolved significantly over time. Many α and β level resources are used in new and unexpected ways to support multiple γ and δ level organizations, systems, and functions. This is often seen when new capabilities are developed despite α and β level resources not outwardly changing. One example is the timed release of stored energy. Instead of the simultaneous release of energy, the facility can be modified to release energy in specific patterns and intervals. This allows researchers to further investigate properties not achievable otherwise.

Table 1. ROPE Table for Z

Type	Level	Resource	Operations	Policy	Economics
Network-of-Networks	**Delta (δ)**	Multiple interwoven organizations for a capability (Z-Machine)	Operation of multiple organizations for a capability	Policies related to a given capability	Economics of operating/maintaining a capability (Z-Machine)
	Gamma (γ)	Organization level resources (Pulsed Power Org)	Operating collection of activities/functions	Policies related to performing multiple activities/functions in concert	Economics of operating/maintaining an organization
	Beta (β)	Collection of α resources for common activity/function (ESS Teams)	Operating a resource network for common activities/function (Releasing multiple marx banks)	Policies relating to activities/function (Certifications)	Economics of using multiple assets to carry out activity (Personnel Hours)
Base Level	**Alpha (α)**	Infrastructure & Systems (Marx Banks)	Operating a resource (Charge a Marx)	Policies relating to single resource use (Manuals)	Economics of using a single asset ($/kWH)

The base (α) level of analysis is mostly comprised of readily visible systems and activities, such as marx banks (resources), charging and releasing energy for a single marx (operations), maximum marx charge (policy), and cost of electrical energy (economics). Again, this is one example of a PPF system used for illustration.

A collection of α level systems form a group or network of resources, operations, policy, and economics represented as the β level in the table above. Examples of resources, operations, policy, and economics at the β level are Energy Storage Section (ESS) teams, charging and releasing energy from multiple marx banks (experiment execution), high voltage certifications, and cost of charging respectively. The networks formed by the β go on to form the γ and δ levels.

Higher networks are a combination of various lower ones working in concert. Failure for one network to collaborate, whether due to inability or pursuit of other goals, has the potential to degrade other higher networks or even the overall SoS. This can be seen when key α level resources disrupt the entire network. For example,

Policies at the β level tend to consist of more guidelines and interpretations while other levels depend more on manuals, procedures, and management policies. One example is the troubleshooting of multiple marx banks. Technicians will sometimes opt to select individual marx banks or test entire groups.

Economics, across all levels, is relatively sparse compared to other dimensions due to the lack of data. The primary focus is the number of hours for each day of operation while some emphasis is placed on personnel hours.

5. Discussion

5.1. Challenges in communication and impact on PPF organizational goals

Organizational goals in a PPF are often nuanced and subject to change. Clear communication or translations of higher-level organizational goals to lower groups ensures that priorities remain consistent. A SoS that exhibits CAT dimensions that are loosely connected , autonomous, and more human-based are unlikely to develop a strong coordinated effort to achieve SoS goals without a governing body, regulation, or other forms of oversight [8]. PPFs fall within this category. One metric frequently touched on is the scientific contribution of the work performed. To achieve this, some groups have interpreted this as the prioritization of *volume* of experiments executed each year. Other groups have focused on increasing the scientific value for each experiment. Although both approaches are equally valid, higher-level group (management) interventions are required to ensure that the overall mission is met through a balance of both approaches.

Socio-technical perspectives could provide insight on how to better navigate PPF environments [16] [17] [18] [19]. Such approaches would highlight that it is critical for management to continuously communicate organizational goals, but also reevaluate if and how goals are to be met.

5.2. How Z is evolving as a PPF

Z is constantly undergoing change to adapt to national and scientific needs. However, the results of the SoS analyses indicate that there is little focus in driving change at the lower levels if priorities at the higher levels eclipse basic operational needs and efficiencies. In order to achieve SoS goals more effectively, Z has investigated securing resources, improving operations, and understanding economics at the α and β levels. These efforts aim to shift Z as a PPF from low to high connectivity and towards more technological systems.

Although Z continues to operate daily, many of the parts required to maintain the various systems are becoming more resource intensive, increasingly prohibited, or obsolete. One such resource seldom mentioned in prior technical analyses is a qualified workforce. The type of training needed to work safely and proficiently in a PPF is very intensive; the average technician is expected to spend 2 months in training before being qualified to perform basic tasks. It is expected to take another 4 years before becoming qualified to load an experiment. Results indicate that additional investments should be made to reduce the amount of time required to develop technicians and leverage other systems that require less training.

Standardization and integration at Z have become increasingly important as the complexity of the varied systems coupled with the diversity of hazardous environments continue to grow. Shifting from human to more technological systems provides an opportunity for operations to better navigate new and existing hazards. The use of automation tools in operations show significant promise in limiting hazard exposure. However, the SoS analyses indicate that stakeholder identification and scoping of work are critical steps in the success of these efforts.

One way to address standardization and integration efforts in to pursue a modular approach to reduce costs of heterogenous systems at the α and β levels. However, the author notes that, as systems become more coupled, small deviations could lead to cascading failures. This tendency should be considered when designing new systems at the lower levels of the SoS hierarchy.

5.3. Actionable Insights at Z

PPFs like Z are under pressure to produce scientific contributions with decreasing or stagnant budgets coupled with the growing complexity in making new discoveries. In order to reach output expectations within the given constraints, investments in understanding these organizations in the context of SoS frameworks is vital for both scientific and operational purposes. For instance, acknowledging economic needs and implications provides opportunities to develop business cases in support of reevaluating the cost-benefit of resources or policies. Understanding these risks and opportunities could help an organization better prioritize needs and goals.

Insights gained from the analyses of Z drove the development of two efforts. One project was aimed at shifting Z along the spectrum to a more connected network and more technological topology. The second project focused on improving α and β levels through better resource utilization, more consistent operations, stronger adherence to δ-level policies, and cost reduction.

The first project, inspired by both SoS analyses, was a time estimation program developed to better coordinate complex and varied activities for all Z experiments. Compared to previous approaches, analysis of β level resources and operations have provided more accurate predictions for task execution. The program was able to account for emergent behaviors that were missed using other scheduling tools. For instance, analysis across experiments resulted in the identification of key milestones that could be used as a measurement of potential issues or delays. This program is currently used as a core product in scheduling activities and provides a proactive approach to ensure that experiment execution is better resourced in terms of time, personnel, and equipment.

The second project used outputs from ROPE table to develop and deploy an automated refurbishment tool.

Refurbishment is a daily process that requires exposure to hazardous environment and intensive manual labor, lasting up to 3 hours with four (4) people. Automating aspects of the process improves the safety and efficiency of operations through significant reductions in exposure time to hazardous environments, which supports γ-level hazard reduction policies. Scaled prototypes have shown the ability to refurbish components back to their original state with fewer defects than previous approaches. Once fully scaled, the automation tool is expected to utilize 50% fewer technicians in a fraction of the time.

Although these projects are still ongoing, several have already seen success in adoption and use. ROPE and CAT were useful in identifying opportunities to improve Z operations while working within the complexity of a SoS. These are two examples of how SoS frameworks can inform analysis and impact management decisions in evolving and tightly coupled systems.

5.4. Future Work for PPFs

The ROPE table suggests a strong teaming component in PPFs. Creating and executing a novel experiment requires the collaborative effort of several groups across multiple levels of the organization. With the data from an experiment as the overarching goal, stakeholders must communicate needs and expectations while also achieving compromise with other groups. This allows for continuous output across a diverse set of scientific programs.

The above observation is an example of how lower-level networks work in concert to meet higher-level objectives. Due to managerial and operational independence of the SoS, failure to collaborate or negotiate has the potential to degrade the performance of the PPF by withholding shared or limited resources. This can lead to longer development times or incomplete solutions.

Further research in other SoS applications on inter-organizational collaboration could provide new ideas for improving this aspect of PPFs. Healthcare is an SoS that is different than PPFs in autonomy but similar in other CAT dimensions. For example, a hospital network offers insight into how heterogenous high-performing groups coordinate to provide consistent, high quality care to patients in a distributed geographic area with varied access to resources and technological systems. A study that compares PPFs and hospital networks might highlight opportunities for PPFs to achieve the same level of success in collaboration.

6. Conclusion

PPFs are currently under pressure to increase capability and scientific with less time and resources; this has resulted in technical, managerial, and operational complexity indicative of system-of-systems structures and behaviors. This paper demonstrated potential uses for SoS frameworks in applied operational settings. Results prioritize and decouple challenges from a holistic perspective such that traditional approaches can be more effectively applied. Stakeholders can then view challenges through a different lens and have productive conversations to identify insights about relevant factors at other levels of the organization.

7. Acknowledgements

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

The author is grateful to Megan Nyre-Yu for her feedback and encouragement.

8. References

[1] D. Clery, "Fusion Power's Road Not Yet Taken," 11 October 2011. [Online]. Available: http://science.sciencemag.org/content/334/6055/445.

[2] A. Cho, "Senate Budget Bill Holds Energy Department Science Level," 9 September 2011. [Online]. Available: http://www.sciencemag.org/news/2011/09/senate-budget-bill-holds-energy-department-science-level.

J. Mervis, J. Kaiser and E. Kintisch, "House Approves Flat 2011 Budget for Most Science Agencies," 9 December 2010. [Online]. Available: http://www.sciencemag.org/news/2010/12/house-approves-flat-2011-budget-most-science-agencies.

[4] M. A. Schaffner, "A Simple Temporal Network For Coordination of Emergent Knowledge Processes in a Collaborative System-of-Systems," in *16th International Conference on Accelerator and Large Experimental Physics Control Systems*, Barcelona, 2016.

[5] M. W. Maier, "Architecting Principles for Systems-of-Systems," *Systems Engineering,* pp. 267-284, 1998.

[6] D. A. DeLaurentis, W. A. Crossley and M. Mane, "Taxonomy to Guide Systems-of-Systems Decision-Making in Air Transportation Problems," *Journal Of Aircraft,* pp. 760-770, 2011.

[7] A. Gorod, B. Sauser and J. Boardman, "Systems-of-Systems Engineering Management: A Review of Modern History and a Path Forward," *IEEE Systems Journal,* pp. 484-499, 2008.

[8] J. Gandhi, A. Gorod and B. Sauser, "A Case Study: The New York City Yellow Cab Systems of Systems," in *2011 6th International Conference on System of Systems Engineering*, Albuquerque, 2011.

[9] M. A. Schaffner, "Extensions of a Simple Temporal Network Coordinating Emergent Knowledge Processes in a Collaborative System-of-Systems," in *The 28th International Conference on Automated Planning and Scheduling*, Delft, 2018.

[10] K. M. Matzen, "Topical Fusion," *Nature,* pp. 598-599, 1980.

G. Yonas, "High-Output Sandia Accelerator Able to Predict Nuclear Blast Physics," 2 December 1996. [Online]. Available: http://www.sandia.gov/media/zpinch.htm.

[12] R. B. Spielman, S. F. Breeze and C. Deeney, "PBFA Z: A 20-MA z-pinch driver for plasma radiation sources," in *Proceedings of the 11th International Conference on High-Power Particle Beams*, Prague, 1996.

[13] M. Reynolds and S. Holwell, "Introducing Systems Approaches," in *Systems Approaches to Managing Change: A Practical Guide*, London, Springer, 2010, pp. 1-24.

[14] A. P. Sage and C. D. Cuppan, "On the Systems Engineering and Management of Systems of Systems and Federations of Systems," *Information-Knowledge-Systems Management,* pp. 325-345, 2001.

D. A. DeLaurentis and R. K. Callaway, "A System-of-Systems Perspective for Public Policy Decisions," *Review of Policy Research,* pp. 829-837, 2004.

[16] F. E. Emery and E. L. Trist, "The Socio-technical System as a Source Concept," in *6th International Conference of the Institute of Management Sciences*, Paris, 1959.

[17] E. L. Trist, The Evolution of Socio-Technical Systems, Toronto: Ontario Ministry of Labour, Ontario Quality of Working Life Centre, 1981.

[18] G. Baxter and I. Sommerville, "Socio-Technical Systems: From Design Methods to Systems Engineering," *Interacting with Computer,* pp. 4-17, 1 January 2011.

[19] E. Mumford, "The Story of Socio-technical Design: Reflections on Its Successes, Failures and Potential," *Info Systems,* pp. 317-342, 2006.