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A FRAMEWORK FOR ANALYSIS AND DESIGN OF DYNAMIC AD HOC SOCIO-TECHNICAL SYSTEMS

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ABSTRACT

Ad-hoc systems are socio-technical systems emerging in response to dynamic problematic situations. These systems form when situation systems interact with respondent systems organized by human agents using elements available in the situation and assets brought in from outside the situation. The immediacy of formation, fast evolution, and short lifecycles of ad-hoc systems intertwine design, implementation, and operation activities in complex ways not addressed by current approaches to Systems Engineering focusing on more sedate environments.

The proposed framework presents a language for classifying fundamental building blocks of ad-hoc systems – single-agent intervention, staging, readiness, and development systems. Further classification according to the physical location of agents and assets relative to situations generates 16 system classes on the 4x4 matrix of Ad-hoc Systems Gameboard, which is a helpful tool for managing the evolution of system portfolios. Combining the Gameboard with mapping the systems onto the PSI matrix reveals additional relationships and evolution patterns, opening up promising directions to address the challenge of designing, planning, and implementing interventions in complex situations.

Keywords: Systems Engineering (SE), Design methodology, Multi- / Cross- / Trans-disciplinary processes, Socio-Technical Systems, PSI methodology

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1 INTRODUCTION

People or organizations respond to situations by continuously assembling, evolving, and disassembling heterogeneous ad-hoc systems, using tools and elements of the situations themselves. This everyday activity of responding to situations includes elements of ad-hoc design and implementation not covered by Systems Engineering research and practice.

The success of the response hinges on people's ability to align their systems with the reality of evolving situations and to leverage diverse assets, skills, and capabilities. The PSI framework (Reich & Subrahmanian, 2022) introduces several concepts and tools for analyzing different kinds of alignment – the Problem, Social, and Institutional (PSI) spaces for analyzing systems, the PSI matrix for helping to drive systems evolution seen as the alignment of the spaces with ever-changing situations and goals, and the PSI network for joint alignment of multiple systems. The current application of the PSI framework focuses on a relatively slow process of moving from a misaligned system to a new stable aligned situation and does not address ad-hoc systems.

This paper presents a framework for understanding ad-hoc systems as dynamic and short-living systems and proposes tools for understanding and managing the alignment of these systems with emerging and evolving situations.

This paper is structured as follows. Section 2 introduces ad-hoc systems as a distinct class of socio-technical systems. Section 3 characterizes ad-hoc systems by introducing situation and intervention systems. Section 4 presents single-agent ad-hoc systems as fundamental building blocks and classifies them according to two schemes. Section 5 provides the PSI interpretation. Section 6 introduces a prototype for the response management tool based on the classifications. Section 7 concludes the paper and outlines the direction for future research.

2 BACKGROUND

2.1 Socio-technical systems

Every functioning system must include human and non-human elements. There are many approaches to researching, describing, and explaining integrated technical and social systems, such as actor-network theory (Law, 1992), socio-materiality (Orlikowski, 2007), and routine dynamics (Pentland *et al.*, 2012), but these approaches provide no significant engineering design perspective. Socio-Technical Systems Engineering is the primary discipline focusing on the collaborative design of technical and social systems.

The concept of Socio-Technical Systems originated during World War II in the research at the Tavistock Institute in London (Trist, 1981) to integrate social and technical aspects in studying and designing work organizations (Frans & Tien, 1990). In the 1990s, the concept was imported to the discipline of Information Systems to help design organizations reliant on computers and software (Whiteside et al., 1991). In late 1990, the socio-technical system approach was applied to information systems (Sutcliffe & Minocha, 1999; Sutcliffe, 2000). In the late 2000s, Socio-Technical Systems Engineering emerged (Baxter and Sommerville, 2011, 2012) by integrating the socio-technical approach with Systems Engineering methods for designing information systems supporting organizations.

2.2 Sustained and respondent systems

Lawson (2010) distinguishes between sustained, respondent, and thematic socio-technical systems. Sustained systems are institutionalized entities existing over long periods and focusing on such purposes as provisioning products (aircraft, telecommunication equipment, or medical equipment) or supplying services (transportation, communication, or health care) over a long-sustained lifecycle.

Respondent systems differ from sustained systems as they form in response to situations and are "organized from the available assets (people and equipment) to counteract the situation" (Lawson, 2010, p.22). The System-Coupling Diagram (Figure 1) illustrates that a respondent system forms from assets and then engages a situation system.

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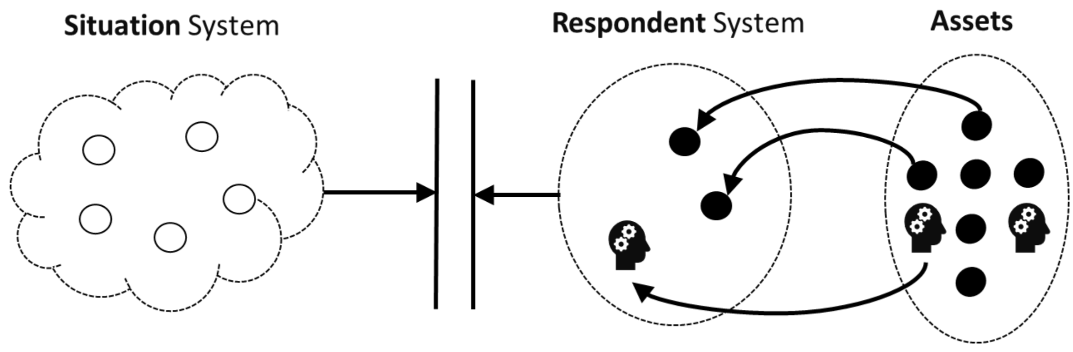

Figure 1. System-coupling diagram reproduced from (Lawson, 2010, p.23).

Thematic systems function as simulations of sustained, situation, or respondent systems for learning about different aspects of these systems. Thematic systems play significant roles in developing real-life systems, as they support the definition, design, construction, and preparation for using these systems.

2.3 Ad hoc systems

Lawson's definition of respondent systems seems to assume they form outside the situation to which they respond, for example, a rescue squad arriving at a building to put out the fire and save as many people and animals as possible. This most common perception of a respondent system excludes systems that emerge from within the situations to which they respond, like extinguishing a kitchen fire using a domestic fire extinguisher, or respondent systems using in situ elements of the situation as resources for the response, such as a firefighter team supplementing their resources using the local water or sand supply.

This paper builds on the concept of respondent systems to define a class of "ad-hoc systems," using a dictionary definition of "ad hoc" as "formed or used for specific or immediate problems or needs; fashioned from whatever is immediately available" and to characterize these systems properly among other systems.

3 CHARACTERIZATION OF AD HOC SYSTEMS

3.1 Situations, agents, goals

This paper assumes a human-centric perspective, in which every ad-hoc system forms around three foundational aspects – agent, situation, and goal. Using the definitions from the American Psychology Association's (APS) Dictionary of Psychology[1], a "situation" means "one or more circumstances, conditions, states, or entities in the environment that have the potential to exert causal influences on an individual's behavior."

In responding to situations, people exercise "agency" ("the state of being active, usually in the service of a goal, or having the power and capability to produce an effect or exert influence.") and thus become "agents" (Figure 2a). Psychologically, there are no situations without agents experiencing them. To change a situation, an agent must set a goal, "the end state toward which a human or non-human animal is striving." Setting a goal provides a purpose for actions but does not assure desired outcomes.

[1] APA Dictionary of Psychology, https://dictionary.apa.org/

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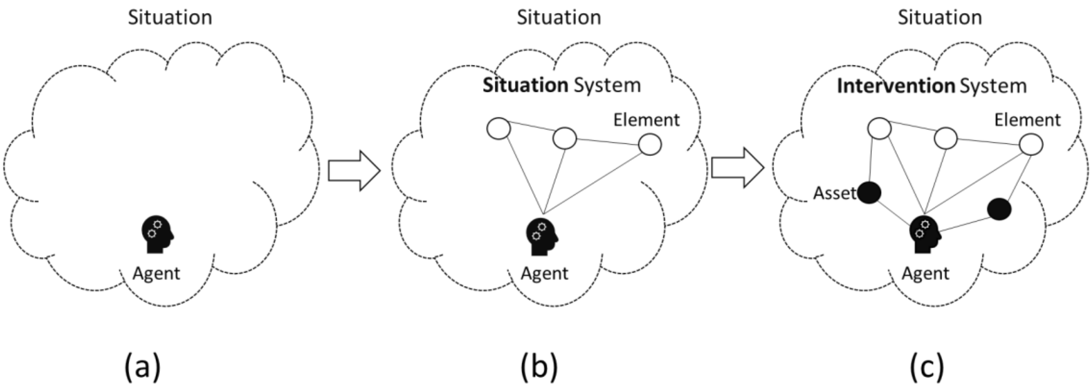

Figure 2. Situations, situation systems, and intervention systems

3.2 Situation awareness and situation systems

To act in situations, the agents must perceive them and become "aware of objects, relationships, and events using the senses, which includes such activities as recognizing, observing, and discriminating." The Situation Awareness Model (Endsley, 1995) defines Situation Awareness as the operator's "understanding of the situation as a whole, forming a basis for decision-making" on three levels: perceiving distinct elements in a current situation (Level 1), synthesizing disjoint elements into comprehension of the current situation (Level 2), and predicting the future behavior and actions of the elements (Level 3).

Situation systems form when agents perceive the situation and establish situational awareness. A situation system is a system that includes all objects, relationships, and events of which an agent (or a group of agents) is aware (Figure 2b, blank circles). Situation systems change and evolve continuously, driven by ongoing changes in the situations and agents' awareness. The situation system is a model of the situation. Only a part of a situation is available for being perceived by agents, and only a part of the available situation is perceived and included in a situation system (Boy, 2015). Improvement in situation perception does not change the situation itself but may change the situation system significantly.

3.3 Intervention systems

To respond to a situation and exercise agency, the agents must transform passively perceived situation systems into intervention systems actively influencing the situation. Agents rarely can "produce an effect or exert influence" directly without using some tools or resources. These tools and resources become "assets," as we appropriate the dictionary definition of a military asset as "something useful to foil or defeat an enemy, such as a piece of military equipment or a spy,"[2] or continuing Lawson's definition of assets as resources available in an organization.

Agents mobilize and organize assets into ad-hoc respondent systems (Figure 2c, filled circles) to attain their goals of responding to situations. When the respondent system engages in the situation, the agents, the assets of the respondent system, and the elements of the situation system interact to form an emergent ad-hoc intervention system that drives changes in the situation (the entirety of Figure 2c).

[2] Merriam-Webster Dictionary, https://www.merriam-webster.com/dictionary/asset

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4 CLASSIFICATION OF FUNDAMENTAL AD-HOC SYSTEMS

4.1 Classification by problem type

Ad-hoc systems are federations of basic ad-hoc systems, each controlled by a single agent. While agents are always concrete, they create different systems when facing concrete situations, preparing for abstract future situations, using available assets, or procuring currently missing assets. From the controlling agent's perspective, these dichotomies create four categories of single-agent systems according to the problems they address, represented by the quadrants in Figure 3.

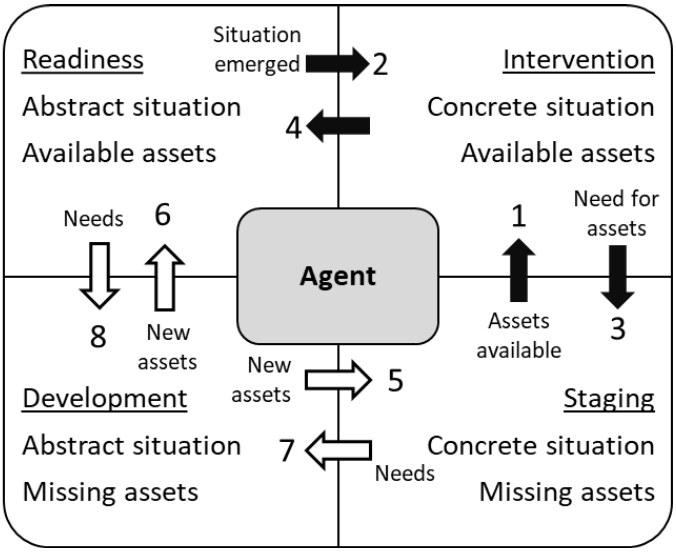

Figure 3. Classification of ad-hoc systems by problem type

The systems in the Intervention category emerge when agents act in a concrete situation employing available assets – a surgical operation on a patient, a search and rescue team looking for survivors in a disaster zone, and ongoing intervention in a jammed traffic situation.

The Staging category describes systems formed by agents organizing the response to the concrete situation before all assets are available (some or all are still missing). The staging systems form when a surgeon plans an operation on a specific patient; a search and rescue team organizes in a staging site, and the police team prepares to deploy to direct traffic. When the staging is done, and assets become available, the agents and the assets can engage the situation and form an intervention system (arrow 1 in Figure 3).

The Readiness category systems wait to respond to (still abstract) situations. These systems are "pre-staged," with agents and all assets available for immediate deployment when the situation becomes concrete. When the situation arises, the readiness system activates, and the action commences (arrow 2 in Figure 3). Examples of readiness systems include emergency surgery rooms and teams waiting for the arrival of accident victims or firefighting teams waiting for deployment.

The agent in an intervention system can decide to halt the intervention and step back into staging (arrow 3 in Figure 3) or readiness (arrow 4 in Figure 3).

The Development category describes systems preparing assets for future systems addressing future situations. The development systems produce capable assets for staging and readiness systems (denoted as white arrows since assets are moving in contrast to systems moving described before, arrows 5 and 6 in Figure 3, respectively). At the development stage, situations are still abstract, and assets are still missing, so the agents must research possible situations and produce descriptions of suitable intervention systems. The needs for new asset development arise from the agents reflecting on intervention experiences that cannot be addressed by the staging or readiness systems (arrows 7 and 8 in Figure 3).

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4.2 Classification by response configuration

Another classification of ad-hoc systems distinguishes between agents or assets physically embedded within a situation and agents or assets engaging the situation remotely. The resulting four combinations categorize intervention systems into four response configuration categories – "In situ," "Support," "Remote control," and "Stand-off" (Figure 4).

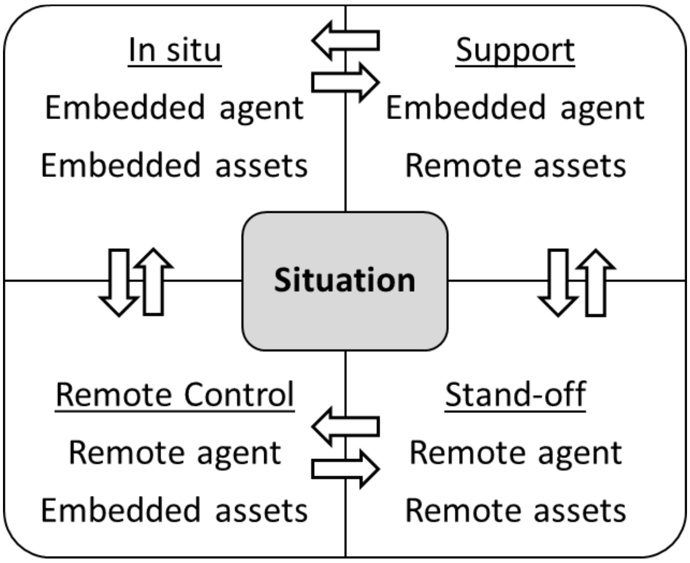

Figure 4. Classification of ad-hoc systems by response pattern

When agents are already inside a situation, they respond using only assets available within the situation, in the "in situ" response pattern. For example, a person can put down a kitchen fire by covering it with a nearby blanket. This local response is immediate and may be very effective, given that the responding person has relevant skills.

The availability of assets near a potential situation significantly enhances the chances of a timely response. When having an opportunity, the embedded agents may import assets from outside the situation (the "support" pattern) and use these assets in combination with the embedded assets. The person responding to the kitchen fire may bring a fire extinguisher from the neighbor. In less urgent situations, an agent lacking the knowledge to respond to a situation may consult an online resource to devise a response.

The "remote control" pattern describes an external agent remotely influencing the situation by communicating with embedded assets. For example, an operator may remotely control security systems in an industrial facility to initiate the lockdown in case of suspected intrusion.

In the "stand-off" pattern, agents and assets assemble outside a situation without any physical influence. This pattern allows for the passive gathering of information about the situation.

Remote assets or agents can enter the situation physically and become embedded, and embedded agents or assets can exit the situation and become remote. The arrows between the quadrants in Figure 6 represent the physical movement of assets and agents entering and exiting the situation.

5 PSI INTERPRETATION

The PSI matrix (Reich & Subrahmanian, 2022) can elaborate on the role of the classification of ad-hoc systems. The PSI matrix includes the agents and assets (social S-space) and practices, organization patterns, and methods (institutional I-space) intended to address changes in evolving situation systems (problem/product P-space) (Figure 5).

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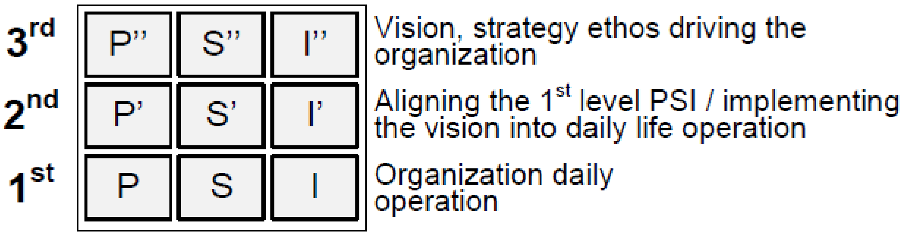

Figure 5. The PSI matrix, Figure 1 from (Reich & Subrahmanian, 2022)

Ad-hoc systems have all three layers – operations, vision, and alignment. A single-agent system may operate at any layer of the overall system, and the single-agent system may also have all three layers. This paper focuses exclusively on the single-agent systems' operations (Layer 1) and does not discuss the upper layers. Still, we use elements of the PSI network (Reich & Subrahmanian, 2019) to present interactions between the systems.

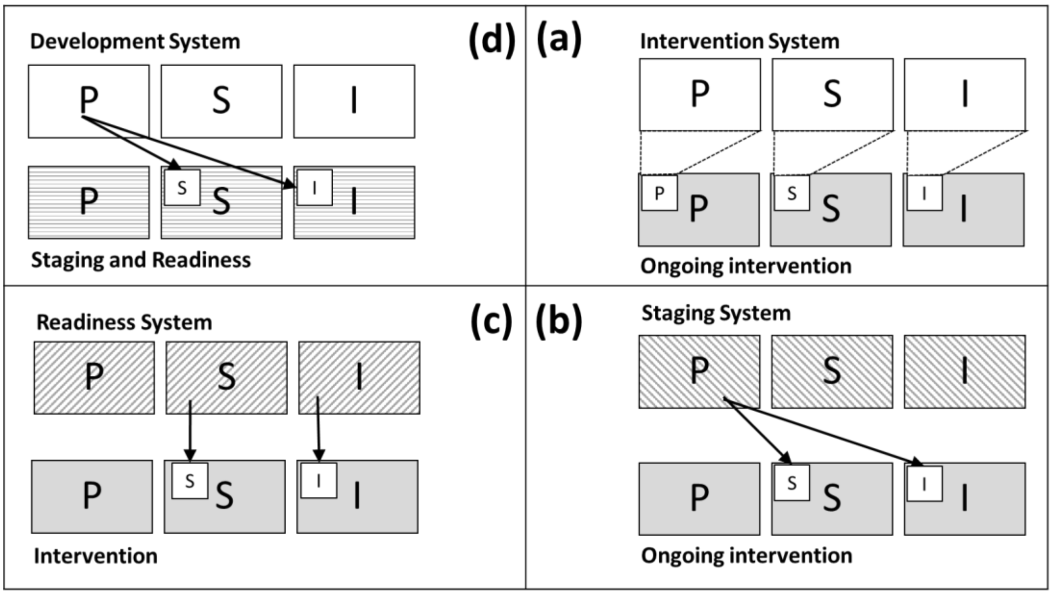

Figure 6. Ad-hoc systems and their relationships on the PSI matrix

A single-agent intervention system's operation spaces (P, S, and I) are embedded in the spaces of the multi-agent intervention (Figure 6a). The intervention systems must continuously use their plans and organization from the I-space and resources in the S-space to influence the P-space with evolving intervention outcomes and situation developments in the larger P-space. Design, implementation, and operation are concurrent, evolving, and intertwined in the intervention systems, with significant improvisation (Hadida & Tarvainen, 2015).

When an abstract situation becomes concrete, the readiness systems become seeds of intervention systems that enter the situation in their entirety so that their agents and assets (in the S-space) and operational routines (in the I-spaces) merge into the S- and I-spaces of the intervention (the arrows in Figure 6c).

In their P-space, the staging systems produce the missing resources (non-human assets and human agents) and plans for ongoing intervention. The resources produced by staging system operations then augment the S-space of the ongoing intervention, and the plans seed the I-space of the intervention (the arrows in Figure 6b).

The development systems produce (in the P-space of their operations layer) resources (agents and assets) and plans for all social and institutional spaces of the staging and readiness systems but not for the intervention systems directly (the arrows Figure 6d). The development systems also supply resources and plans to other development systems and even for themselves.

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6 AD-HOC SYSTEM GAMEBOARD

The categories and examples presented in the previous chapter refer to single-agent ad-hoc systems. Most real-world responses are more complicated, involving multiple communicating, coordinating, and collaborating agents that allocate goals, share or exchange assets, and integrate systems under their control.

The Ad-hoc Systems Gameboard (Figure 7) can be used to plan complicated interventions. The Gameboard combines the classification schemes of Section 4 into a 4x4 matrix in which icons for agents, assets, and integrated systems can fill cells. The vertical arrows between the cells represent all possible transitions of separate agents and assets (blank arrows) as they go from development to readiness and staging and transformations of complete systems (filled arrows), corresponding to Figure 3. The black horizontal arrows represent the physical movement of concrete agents, assets, and systems, corresponding to Figure 4.

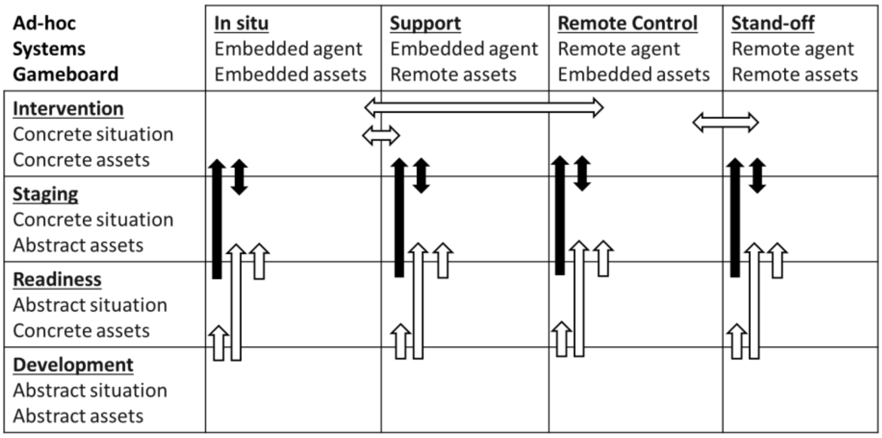

Figure 7. Ad-hoc systems Gameboard

For example, Figure 8 shows how the Gameboard can be used to plan and control the response for a situation by placing agents, assets, and systems in the matrix cells and moving them between cells according to the rules represented by the arrows. In the scenario in Figure 8, the organization faces an intruder event at its facility.

As a situation awareness tool (indicated by filled icons), the Gameboard shows that the organization has the complete remote control readiness CCTV System, ready assets for stand-off Drone Surveillance, partially completed readiness in situ Autonomous Engagement Force missing an asset (Night Vision Goggles) still in development.

As a response management tool, the Gameboard indicates that the organization can intervene immediately using the CCTV System (arrow 1). Meanwhile, the organization can stage the Drone Surveillance (arrow 2) and then add the capability to the intervention (arrow 3). The organization cannot activate the incomplete Autonomous Engagement Force (arrow 4). However, it can improvise and repurpose its agent as an Assisted Engagement Force in a support configuration, in which the agent can engage the intruder not autonomously but with the support and guidance of other systems (arrow 5).

As a development strategy support tool, the Gameboard suggests the urgency of developing the night vision goggles (arrow 6) to complete the Autonomous Engagement Force. On the other hand, it also suggests training a dedicated Assisted Engagement Force (arrow 7) to capitalize on the improvised solution.

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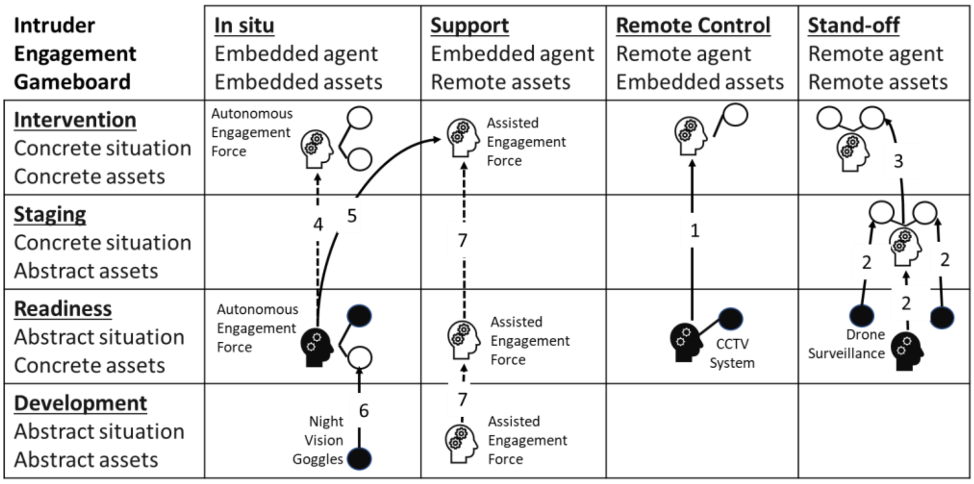

Figure 8. Working with the Gameboard

7 CONCLUSIONS AND FUTURE WORK

This paper has outlined a novel discourse space focusing on a distinct class of socio-technical systems – the ad-hoc systems. These systems form to respond to developing situations, and they differ from other socio-technical systems by having short lifecycles driven by the purpose's immediacy and the situations' dynamics. The immediacy of formation and fast evolution of ad-hoc systems intertwine design, implementation, and operation activities in complex ways not addressed by current approaches to Systems Engineering focusing on more sedate environments.

To start addressing the challenge of designing, planning, and implementing interventions in complex situations, two classification schemes provide a language to characterize single-agent ad-hoc systems as fundamental building blocks of more complicated multi-agent systems. The classification by problem type distinguishes between intervention systems addressing concrete situations with concrete assets, staging systems preparing for intervening in concrete situations, readiness systems sustaining themselves for being available to intervene in situations immediately, and development systems preparing assets and agents for future interventions.

Another scheme classifies ad-hoc systems according to four distinct response configurations. The "in situ" systems emerge from within the situations from agents and assets physically embedded in the situations. The "support" systems strengthen the in-situ systems with remote assets. Remote control systems form by remote agents operating embedded assets. Finally, the "stand-off" systems can monitor the situation from afar and then move in to intervene in the situation actively.
The ever-changing nature of evolving situations creates the need for continuous intervention systems design and implementation. Situation responders integrate their ad-hoc response system with situation systems, forming intervention systems to drive the evolution of problematic situations in helpful directions. The Ad-hoc Systems Gameboard utilizes the classifications to form a 4x4 matrix that can be used to visualize, monitor, plan, and control multi-agent responses to complicated situations.

The current version of the Gameboard is still a crude prototype. In future research, we plan to proceed beyond the first level of the PSI matrix (Reich & Subrahmanian, 2022) and improve the Gameboard design as a response management tool serving at the second level of the matrix. We also plan to use PSI networks (Reich & Subrahmanian, 2019) to analyze various modes of ad-hoc system formation further.

Future research will also seek to integrate the analytic and synthetic apparatuses from diverse schools of thought, such as systems engineering, socio-technical systems engineering, actor-network theory (Law, 1992), and routine dynamics (Pentland *et al.*, 2012).

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