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Employing Model Based Conceptual Design to Identify Test Range Resources Required to Validate the Delivered Solution

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Abstract. During an initial system concept development, systems engineers will look at different areas of the problem space in order to develop a solution that will satisfy the overall capabilities defined by the stakeholders. During this phase, the problem space is intentionally left large in order to consider a larger scope of the solution space and operational environment. Thus, the SE would like to consider as much of the space as possible to determine what is feasible and infeasible when progressing on to the next phase of system development. This paper reports on an extension of Model Based Conceptual Design (MBCD) that visualizes the potential feasible solution space in order to inform decision makers of feasible solutions and test range resources required to validate the delivered solution. An approach is offered, utilizing Design of Experiments methods, to extend previous research on test and evaluation with MBCD as applied to an illustrative use case.

Approach / Outline

Model-based Conceptual Design (MBCD) (MBCD Working Group, 2013) is the application of Model-Based Systems Engineering to the Concept Stage of the generic lifecycle defined by INCOSE (Systems Engineering Handbook Working Group, 2015) that defines the problem space, characterize the solution space, identifies stakeholders' needs, explores feasible concepts and proposes viable solutions. This paper is motivated to continue research in the areas of Model Based Conceptual Design (MBCD) from previous work (Flanigan and Robinson, 2019) to incorporate the Test and Evaluation (T&E) domain and consider how to adjust the T&E in the Concept Phase in order to support successful system development. This paper seeks to extend the MBCD concepts by implementing an analysis of the potential solution space in order to inform decision makers of feasible solutions and test range resources required to validate the delivered solution. This analysis is done intentionally at a higher level of resolution, in order to quickly down select to a smaller set of feasible parameters that could satisfy the problem. Decision makers can be informed on where resources should be allocated in developing the T&E capabilities: system test articles, test range, additional systems, etc.

In this paper we will develop and exercise this analysis process within a defined test case of firefighting and emergency response. Key components that will be analyzed are the test articles (types of structures, spacing, layout), test environment (physical attributes and overall background for the structures), test initiators (fire sources and intensity), as well as the test responders (extinguisher systems, extinguisher sources). Each of these components are parameterized to generate a wide range of representative situations and scenarios to analyze the firefighting capabilities, as well as identify specific parts of the test range to be developed and implemented to successfully host the test event and validate the delivered solution. Through the analysis process, we may be able to identify feasible and infeasible combinations of these parameters in order to draw conclusions on the potential effectiveness for future T&E resources and configurations.

Literature Review

During the development of this paper, we investigated three main topics: MBCD, applications to test and evaluation, and modeling and simulation. These sources were used to identify complementary concepts to leverage for this paper, and others sources were consulted to extend their research areas or capabilities within our concepts, which motivated our additional work.

For MBCD, we leverage Spencer and Harvey's (2014) model-based approach to fire and emergency services, where a capability framework model concept is developed in detail to show traceability between the capability requirements model and the integrated systems model. The capability requirements model contains items such as objectives, user needs, mission tasks, operational activities, limitations, and system functions. These are linked together in order to develop the system requirements that will ultimately satisfy the original user needs and operational tasks. The integrated systems model decomposes the system into smaller areas such as subsystems and solution options. We seek to leverage this concept of traceability to apply to the T&E domain, particularly: "determine and characterise capability", "determine solution-independent needs", and "model existing capability elements and identify capability gaps"; where these three concepts are critical to defining a MBCD-based model for which to analyze the solution space of the T&E capability.

Testing and evaluation of the fire and emergency mission uncovered several sources to assist in the understanding of the critical factors in firefighting effectiveness. Mattsson and Juas (1997) analyze fire and rescue services in Sweden and found that full-time crews have a shorter turn-out time than the volunteer crews, able to service and contain the fire earlier and prevent the damage. Their research includes several building types and firefighting metrics that may be leveraged to assess the MBCD construct. Taylor and Freeman (2010) review other factors in the test environment to include fire movement, intensity, extinguishing concepts, and test range factors such as radiant heat and smoke which may affect the analysis of the fire and extinguishing capabilities.

Simulations are heavily used to evaluate solution spaces, particularly where the initial phase of development can be conceptual in nature, allowing the analyst to explore a wide variety of capabilities, and may actually identify unique and innovative combinations of capability that may not have been originally envisioned, either due to design bias or little knowledge of these compatible capabilities. For example, Raz, Kenley and DeLaurentis (2018) propose an approach (captured in a framework) that can be employed to characterize the implications of high-level design decisions, i.e. the conceptual design. This proposed design space characterization method aims to enable decision makers to evaluate and understand the consequences of system operational, architectural, and design decisions on the system performance.

Fanfarova and Maris (2017) examine the use of simulation within fire and rescue services, particularly in how simulation can improve the firefighting, coordination, and command and control aspects of performing the firefighting mission. Their research explores the reasoning on why M&S can be used to provide a variety of challenging scenarios, be flexible to the user's needs, provide a realistic environment, and improve awareness and efficiency for fire fighters future mission uses. We utilize these concepts to further our development of the firefighting scenarios. Clarke and Miles (2012) utilize analysis to determine the optimum resource allocation and placement of firefighting resources to effectively service their area of responsibility. Their chief complaint was that resource deployment strategies typically relied on professional experience, practice, and modeling. However, with a large number of permutations of scenarios, their existing training software would only allow evaluation of one solution at a time, greatly lengthening the time for which to explore all possible solutions. We use this complaint to explore a design of experiments approach in order to rapidly determine the best solution(s). Taylor and Freeman consult different brushfire prediction models in order to estimate the risk of a wildfire in selected areas as well the rate of fire spread, which we can leverage in our MBCD study. Yassemi et al. study cellular automata models in order to predict the behavior of an element (in this case fire) in the operational environment, which we can leverage to evaluate our parametrization of the solution space. This approach will be similar to employing agent-based modeling techniques to evaluate fire spread based on environments and facility composition, as described by Dorrer and Yarovoy.

Process / Approach Outline

We can then develop our approach towards converting the MBCD artifacts into analysis elements and then perform the analysis in order to understand the viable conceptual design space and the resultant effectiveness of future T&E resources and configurations. The concepts during this development are described below and considers how we apply MBCD principles to define the T&E event before parameterizing variables and establishing the relevant Design of Experiments approach and then finally performing the analysis in order to narrow the solution space and enhance the T&E planning and resourcing.

Apply MBCD Principles to Define the T&E Event

We utilize the MBCD principles to identify pertinent elements of the firefighting problem, namely the extinguishing services, fire starters, and test articles. An example of the overall layout is provided in Figure 1, where buildings that are still intact are denoted in green, extinguisher locations in yellow and fire elements in red. We may choose to populate this layout randomly, by subject matter experts, or load in a selected configuration of buildings and extinguisher locations for further analysis.

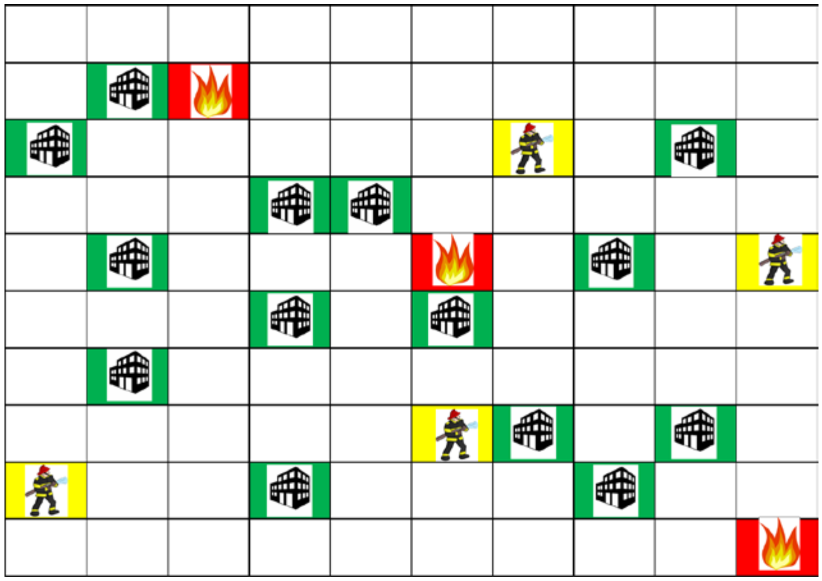

Figure 1. Example Overall Layout

We leverage the MBCD test domain model (Flanigan and Robinson, 2019) to describe the dependencies of different elements that interact within a test event and seek to transform the elements into an analysis task. Figure 2 provides the overall view of the test domain model and an overlaid analysis representation of the elements.

Described by Flanigan and Robinson (2019), these information elements, and their relationships, are traceable to both the Operational Domain and Systems Domain which describes the viable solution space. For example, an "Operational Node" (Fire Extinguisher) is represented by a "Test Article" (Extinguisher under test) which performs in a "Test Event". The rest of the test event can be represented within the test domain model.

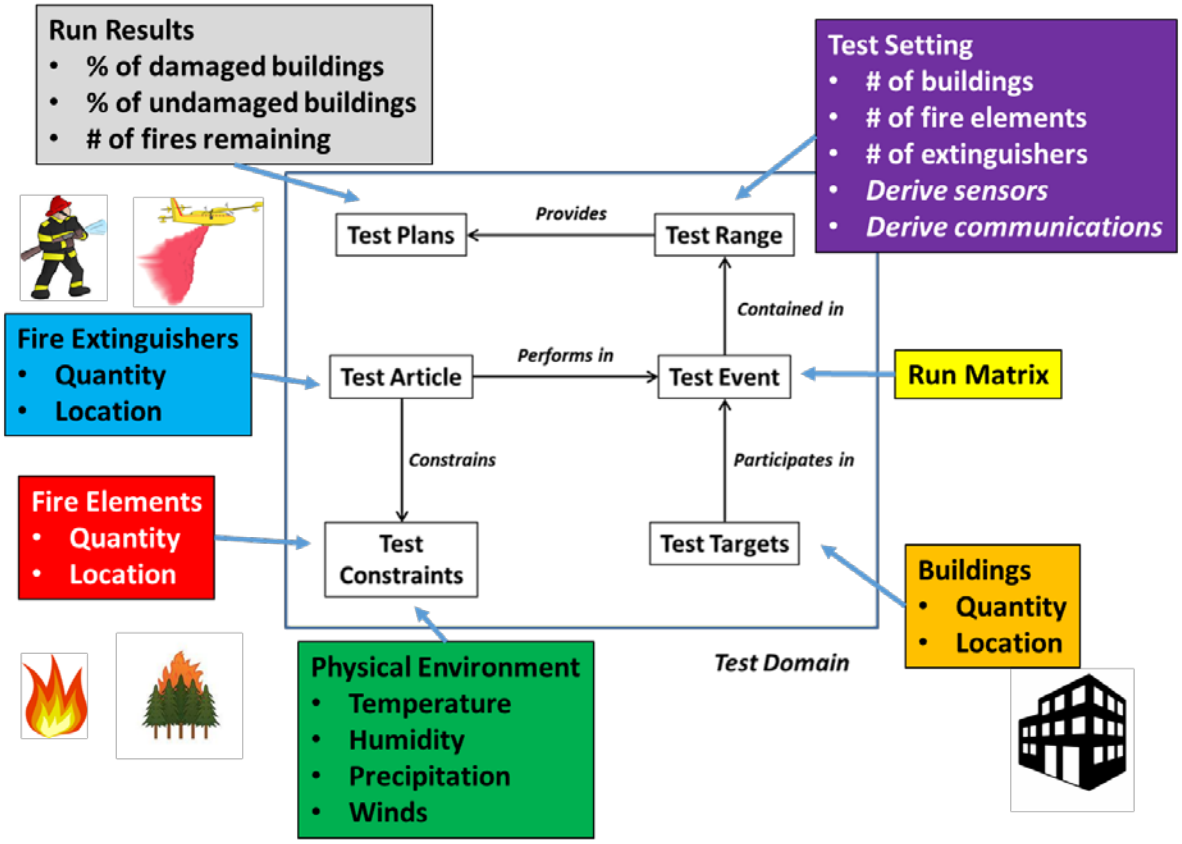

Figure 2. Linkage of Test Domain Model with Analysis Elements

Parameterize Relevant Variables

We can identify critical variables that contribute to the firefighting mission, and parameterize their values in order to model the expected effects based on the threats and extinguishing capabilities. Several simplified variables (for the purposes of easy reading) can include: extinguishing services, which can vary in quantity and available duration. The variables for the fire starters can be quantity and location within the test range. The variables for the test articles can be quantity, type, and relative location to each other. Other physical environment attributes can also include temperature, humidity, wind speed, and precipitation. This parametrization can enable a rapid generation of different combinations of physical and operational factors in order to evaluate a wider solution space and refine the likely T&E resource needs. For the purpose of this paper, we condense the variables to a smaller subset of factors that is described in the analysis section.

Develop the Solution Space (Full Factorial)

We can then develop the solution space which is a full factorial of all combinations of test articles (closeness of articles within 3 environments), physical environment (2 types), fire elements (2 quantities), and extinguishers (2 types) as a means to test our approach in this paper. A more comprehensive approach will be expected to have a larger run matrix, however for the test of this approach, the entire simplified run matrix only consists of 3*2*2*2=24 unique combinations, which is provided in Table 1. This incorporates three building settings for numbers of buildings and density (urban, suburban, and rural); weather effects that decrease or increase the effectiveness of both fire and extinguishers (low / high); fire elements that affect the number of elements (low / high); extinguisher elements that affect the number of elements (low / high).

Table 1: Example Run Matrix

Run	Buildings	Weather	Fire	Extinguishers		Run	Buildings	Weather	Fire	Extinguishers
1	Rural	Low	Low	Low		13	Urban	High	Low	Low
2	Rural	Low	Low	High		14	Urban	High	Low	High
3	Rural	Low	High	Low		15	Urban	High	High	Low
4	Rural	Low	High	High		16	Urban	High	High	High
5	Rural	High	Low	Low		17	Suburban	Low	Low	Low
6	Rural	High	Low	High		18	Suburban	Low	Low	High
7	Rural	High	High	Low		19	Suburban	Low	High	Low
8	Rural	High	High	High		20	Suburban	Low	High	High
9	Urban	Low	Low	Low		21	Suburban	High	Low	Low
10	Urban	Low	Low	High		22	Suburban	High	Low	High
11	Urban	Low	High	Low		23	Suburban	High	High	Low
12	Urban	Low	High	High		24	Suburban	High	High	High

Consider the Infeasible Combinations

In some cases, there may be a design concept that has combinations that do not correctly represent a valid system test concept. A notional example is a ski resort that operates in both desert and winter-like conditions or at the urban fringes where you can observe both urban and rural attributes in the same zone. These combinations can then be filtered out and removed before it provides unexpected and erroneous results.

There are likely to be some infeasible combinations of parameters included in our run matrix that may not be representative of actual firefighting performance and tactics. In this case, we may rely on subject matter experts (SME) to identify these runs and remove them from consideration; however the benefit of using the entire matrix is to analyze all types of permutations which may lead to unexpected and innovative techniques. For the purpose of this paper, we will analyze all combinations of the run matrix.

Develop Rulesets for Analysis

We can then develop rulesets for the analysis of the run matrix; we have simplified this step for the purposes of this paper. We start with the extinguishers and look at the adjacent 8 spaces around the extinguishers for fire sources – if these exist and can be considered extinguishable under the existing environmental conditions, then the fire can be considered extinguished. The next ruleset applies for the fire elements – we can look at the adjacent 8 spaces around the fire location and if a test article is present and follows the same rulesets, it can be removed and converted into a separate fire element with the existing ruleset. The MATLAB-based simulation then continues until the number of timesteps is exhausted, where we can perform a count of the remaining test elements and fire sources.

Other rulesets that may be applied are the effects that the physical environment may have on the fire spread and extinguisher effectiveness. Certain environmental conditions (e.g. higher temperatures, lower humidity, and higher winds) may enable the fire to increase in propagation. We may represent this in our simulation by adding some stochastic performance to the adjacent spaces around the fire and extinguisher locations. As this stochastic behavior may be more representative of conceptual analysis for fire propagation, higher fidelity physics-based models should be consulted for actual fire propagation behavior.

Perform Analysis of Solution Space

We can then analyze the solution space using our rulesets and newly created run matrix. This may provide some insights in how the modification of selected parameters will have an effect on our performance. This will in turn provide insight to the decision makers on how the test may be structured and likely additional resources required for an appropriate level of T&E. An example of an output is provided in Figure 3 to show the buildings before (top left) and after the simulation run (bottom left). The buildings that remain are highlighted as a blue square, whereas the buildings that have burned have turned into a red asterisk. The fires that have been extinguished are indicated as a black asterisk. The simulation will also keep count of the number of buildings and fires that are active throughout the simulation (bottom right), as well as keeping a count of the percentage of still standing buildings (top right). This can lead insight into the timing and spread of fires into the areas of the simulation.

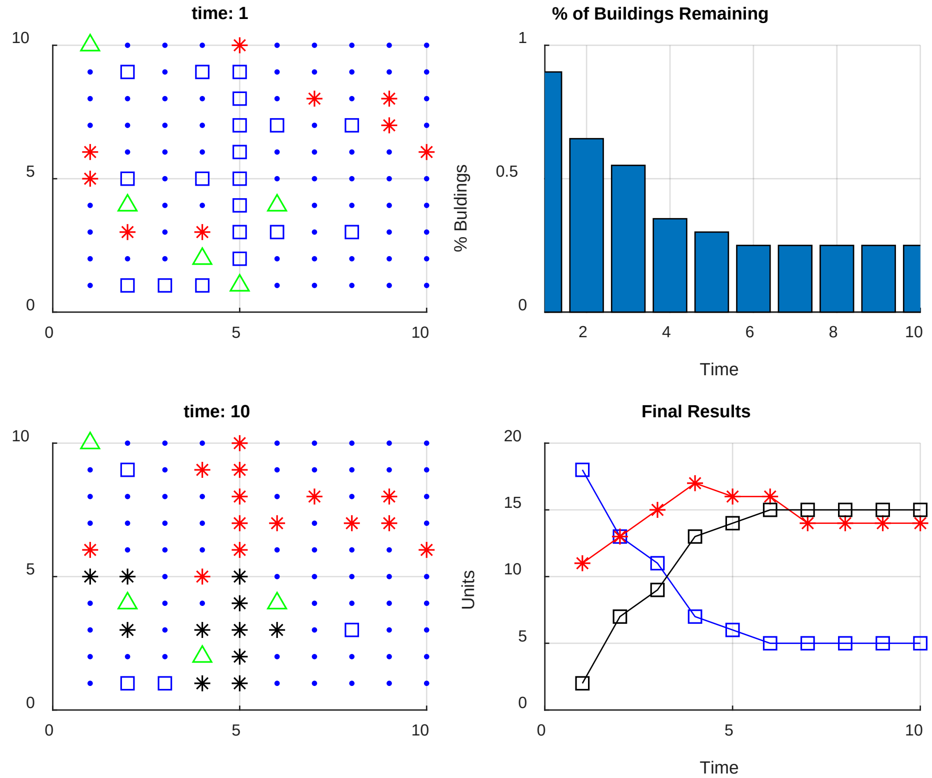

Figure 3. Example Output

Analysis Results

We can exercise this approach using the full factorial run matrix and analyze the extinguisher performance based on the scenario settings. The full factorial is a 24 run design that incorporates three building settings for numbers of buildings and density (urban, suburban, and rural); weather effects that decrease or increase the effectiveness of both fire and extinguishers (low / high); fire elements that affect the number of elements (low / high); extinguisher elements that affect the number of elements (low / high). The outcome (response) is the % of remaining intact and untouched buildings after the scenario run is over. Figure 4 provides examples of four runs from the 24 run set; note the lower right quadrant to show the time-ordered change in undamaged buildings, damaged buildings, and fire elements. Through the use of different setups and performance, this can show a wide variety of time-ordered performance.

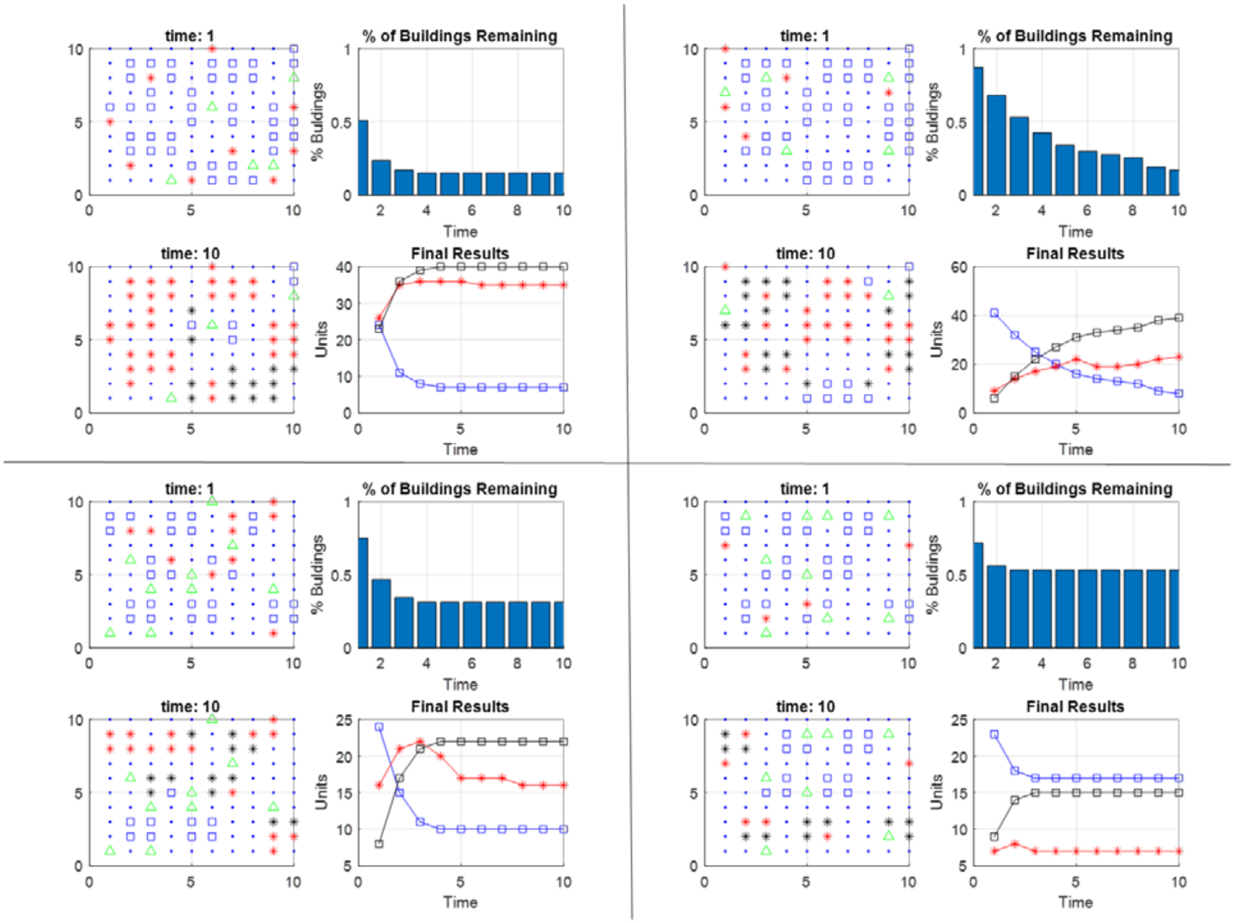

Figure 4. Example Outputs of Run Matrix

The scenarios were executed and analyzed using SAS JMP 13 (https://www.jmp.com/en_us/home.html) which is a commonly used statistical software package. Using a least squares regression analysis, the R-squared value (a statistical measure to represent the proportion of variance of a dependent variable to be explained by an independent variable in a regression model) was 0.82, which indicates a good fit of the data (approximately 82%). Table 2 provides a listing of the factors (both single and cross-factors) that had a significant effect on the overall response of % intact buildings. The highlighted values of buildings, fire, extinguishers, and weather * fire were significant to the overall performance. With our simple example these are intuitive as being critical factors to influence the firefighting performance, and therefore informs decision makers that the T&E planning should focus on ensuring that adequate resources are allocated to building (test target) and fire types (test constraints) representation.

Table 2: Significant Effects

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Buildings	1	1	0.09378906	13.4033	0.0029*
Weather(1,2)	1	1	0.00032878	0.0470	0.8318
Fire(1,2)	1	1	0.18627189	26.6198	0.0002*
Extinguishers(1,2)	1	1	0.07984625	11.4107	0.0049*
Buildings*Weather	1	1	0.00472656	0.6755	0.4260
Buildings*Fire	1	1	0.00097656	0.1396	0.7147
Weather*Fire	1	1	0.03935049	5.6235	0.0338*
Buildings*Extinguishers	1	1	0.01196289	1.7096	0.2137
Weather*Extinguishers	1	1	0.00016835	0.0241	0.8791
Fire*Extinguishers	1	1	0.00335538	0.4795	0.5008

How This Approach May be Applied to Narrow the Solution Space to Enhance T&E Planning and Resourcing

This approach can be utilized to help the decision makers and testers to distinguish the most likely final delivered solution, i.e. to differentiate the well-performing system configurations from lesser-performing configurations. By performing this analysis in a quick-turn format, we can guide where resources should be prioritized and assigned in developing the T&E capabilities. Additionally, we may then be able to focus on a smaller subset of the run matrix and evaluate it in greater detail, for example build prototype test environments or targets. Figure 5 provides a conceptual view of the original run matrix of the test combinations with a higher performance, defined as a larger percentage of unburned buildings remaining after the simulation has finished. In this example, we select runs that have 40% or greater unburned buildings as indicating a promising extinguisher system for further evaluation. The test environment for validating the solution needs to include these test combinations (or a further sub-set).

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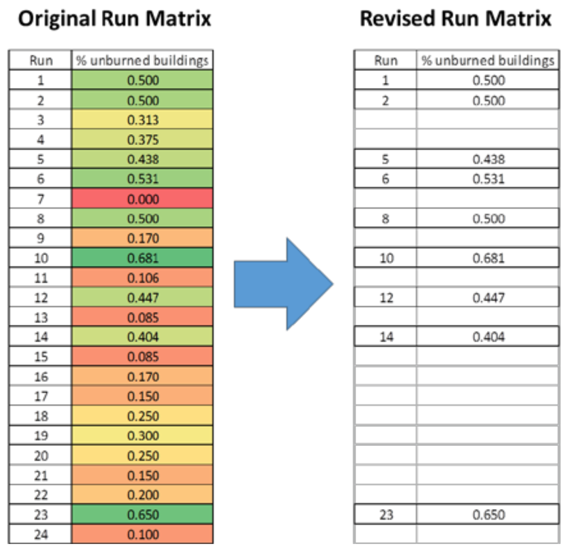

Original Run Matrix

Run	% unburned buildings
1	0.500
2	0.500
3	0.313
4	0.375
5	0.438
6	0.531
7	0.000
8	0.500
9	0.170
10	0.681
11	0.106
12	0.447
13	0.085
14	0.404
15	0.085
16	0.170
17	0.150
18	0.250
19	0.300
20	0.250
21	0.150
22	0.200
23	0.650
24	0.100

Revised Run Matrix

Run	% unburned buildings
1	0.500
2	0.500
5	0.438
6	0.531
8	0.500
10	0.681
12	0.447
14	0.404
23	0.650

Figure 5. Example of Solution Space Narrowing

Summary

This paper demonstrated the viability of utilizing MBCD artifacts, supported by mathematical analysis, to better define and prioritize Test and Evaluation resources earlier in the systems lifecycle that is applicable across different domains. Through a simplified example it evaluated the different viable solutions concepts, captured in combinations of the firefighting elements and behavioral rulesets, to identify a set of preferred test and evaluation configurations and their implication of the validation of the final delivered solution. This could provide insight for multiple stakeholders to determine next steps in the system development cycle and the planning for future T&E activities.

Next Steps

Next steps could incorporate higher fidelity simulations as the viable solution set narrows as the system concept matures. Increasing this simulation fidelity through aspects such as fire spreading dynamics, or incorporating higher fidelity building materials and atmospheric effects, will generate more realistic results, which would naturally provide greater clarity on the optimum T&E concept as the system concept matures.

Other simulations considered could be agent-based models, system dynamics, discrete event simulations, or system thinking to aid in additional modeling.

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Biography

David Flanigan. David Flanigan is a member of the Principal Professional Staff for The Johns Hopkins University Applied Physics Laboratory, providing systems engineering services to various Department of Defense and Department of Homeland Security clients, and has 20 years of active duty and reserve service with the US Navy. A graduate of the University of Arizona, he holds a MS in Information Systems and Technology, a MS in Systems Engineering from the Johns Hopkins University, and a PhD in Systems Engineering and Operations Research from George Mason University. Dr. Flanigan is a member of INCOSE, INFORMS, and MORS.

Kevin Robinson. Kevin Robinson is the Chief Engineer at Shoal Engineering with a distinguished career in the field of Guided Weapons in both the UK's Ministry of Defence and Australia's Department of Defence. He has made significant contributions to the development of advanced guided weapons through modelling and analysis, research, and leadership of large cross discipline teams. Throughout his career, Kevin has taken a leadership role in advancing the field of Model-Based Systems Engineering (MBSE) via his publications and contributions to the systems engineering community. He initiated and chaired Australia's first annual MBSE Symposium, formed and chaired INCOSE's Model-Based Conceptual Design Working Group, delivered a keynote address to INCOSE's international symposium in 2016, and has made contributions to INCOSE's Systems Engineering Handbook and related standards. Recently he has joined INCOSE's Future of Systems Engineering initiative core team.