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TOOLS, CAPABILITIES AND EXPERIENCE OF DIGITAL TWINS AT THE MITRE CORPORATION

Edward Y. Hua[1], Jon Cline[1], Robert Wittman[1], and Bianica Pires[1]

[1]Simulation, Experimentation, and Gaming Department, The MITRE Corporation, McLean, VA, USA

ABSTRACT

The technology of Digital Twin (DT) engineering is increasingly being leveraged in industry for a wide range of applications. More recently, many departments in the U.S. government are exploring the use of DT to support their respective mission mandates. The MITRE Corporation, as a Federally Funded Research and Development Center (FFRDC), is actively developing DT tools and capabilities to meet the needs of its government customers. While more people are becoming familiar with the term "Digital Twin," not everyone has a clear understanding of what it is, and how it is implemented in different applications. In this paper, we present some of these DT tools and capabilities, as well as some MITRE projects that have benefitted from the DT toolset. Additionally, we discuss several nascent areas where DT may bring greater value to MITRE customers.

1 INTRODUCTION

Rapid advances in a multitude of diverse fields, such as Artificial Intelligence (AI), High Performance Computing (HPC), and 5G/6G wireless communications, are fueling the research and development of digital transformation. Digital transformation seeks to maximize the use of digital technologies in various stages of an organization's operations, leading to revolutionary ways of improving organizational efficiency, raising greater situational awareness among stakeholders, and delivering greater value to its customers. Indeed, Vial (2019) defines it as "the process that aims to improve an entity by triggering significant changes to its properties through combinations of information, computing, communication, and connectivity technologies." Coincidentally, the increasing interest in digital transformation in the research community aligns with the rise of Digital Twin (DT), with the latter serving as an enabling tool to realize the vision of the former.

A Digital Twin is a virtual replica of a physical entity (e.g., a system, process, or service) that exists in the real world (Fuller et al. 2020). The DT is connected with its physical counterpart through a two-way data exchange mechanism. Live data from the physical entity is collected and transmitted to its DT for predictive, even prescriptive, performance analysis. Such analysis allows the DT to generate an accurate operational state of the physical entity in real time, and, if necessary, suggest a remedial course of action to forestall potential hazards that could lead to performance degradation or system malfunction. Such mitigatory strategies will then be transmitted from the digital replica back to the physical entity for solution implementation.

This conceptual model of the DT was first formalized in 2002 by Michael Grieves (2002), who proposed it as a viable tool supporting product lifecycle management (PLM). The term "Digital Twin" did not enter the lexicon until 2009, when John Vickers of the National Aeronautics and Space Administration (NASA) coined the term, which has since become widely accepted. In recent years, thanks to the explosive growth of the Internet of Things (IoT), realizing the many strengths envisioned for DT has become possible, and it has garnered considerable attention in the modeling and simulation (M&S) research community. Small, inexpensive, and smart sensors can be embedded in a physical entity at scale to collect and transmit real-time data to the DT, as well as receive information from it to actuate the desired system reconfiguration.

DT is not a single technology; rather, it is supported by a suite of capabilities that enable various functionalities, including, but not limited to, modeling and simulation, data collection, data transfer, data fusion, verification and validation, predictive/prescriptive operational analysis, and data visualization. There is ongoing research to develop these tools and integrate them into a DT framework.

Academia and industry have made great strides in researching DT and exploring its applications. The U.S. government, more recently, is showing increasing interest in leveraging DT to support its vision of digital transformation. The MITRE Corporation, as a Federally Funded Research and Development Center (FFRDC), has been actively developing DT tools that can realize relevant capabilities to support its government customers. Some of these tools were developed through MITRE’s internal research and development (R&D) efforts, while others have been developed to support projects from multiple domains. In this paper, we have compiled a list of capabilities and their enabling tools that address different aspects of a DT, as well as their applications for different customer needs. Note that this does not constitute a complete list of tools and capabilities that span all aspects of a DT, nor is it a complete list of all DT work at MITRE, but it serves as a representative sample to promote closer coordination of the R&D endeavors between academia, industry, and the government that solve complex problems facing the Nation.

The remainder of this paper is organized as follows. Section 2 presents the DT capabilities and their enabling tools that MITRE is developing or has developed. Section 3 discusses some MITRE projects and research efforts. Section 4 discusses future work on DTs that may bring greater value to MITRE customers. Section 5 concludes the paper.

2 DIGITAL TWIN TOOLS AND CAPABILITIES

Digital transformation greatly improves the performance, robustness, and timeliness of simulation methodologies. As a key enabler of digital transformation, DT has been applied in a wide array of industries and sectors, such as advanced manufacturing, smart city planning, utilities, and healthcare. The continued research breakthroughs in academia and the expanding applications in industry have demonstrated to the U.S. government that DT is fast becoming a new paradigm that complements, rather than replaces, traditional modeling and simulation methodologies. As such, government agencies are now actively pursuing ways to leverage DTs in support of their mission mandates through data-driven, simulation-based analytical studies with potentially real-time data exchange and update rates.

In recent years, MITRE’s Modeling and Analysis Innovation Center (MAIC), which the authors of this paper are members of, has undertaken a number of internally funded research projects to explore and develop various DT capabilities. In addition, MAIC supports a number of U.S. government customers with its M&S expertise to develop data-driven, simulation-based solutions that address the problems facing these customers. Many of these solutions are enabled by popular, open-source software tools (e.g., Python); others exploit the existing features of current simulation tools used by the government and industry (e.g., OneSAF and Unreal Engine, respectively). These projects allow MITRE to develop and refine the relevant DT capabilities, as well as train the MAIC staff to master the use of these tools.

Table 1 presents the DT capabilities and their enabling tools that have been applied in multiple endeavors at MITRE. This table by no means presents a complete list of MITRE capabilities and tools that cover all aspects of a DT. The capabilities are classified into several types, such as data visualization, big data analytics, and distributed simulation and interoperability. It can be seen that DT capabilities are flexibly implemented, as any one capability can be enabled by more than one tool; the choice of the tool largely depends on the resource availability of a project (e.g., whether the project needs to be run on a certain platform or whether the project team is familiar with one tool over another). A key lesson learned for successfully creating and using DTs is that the tool used to implement a certain function of the DT is of less consequence, the effective integration of the selected tools across or within all of the associated DT functions is what matters.

One of the capability types within the DT modeling and simulation function is behavior modeling. Behavior modeling plays an important role in M&S in that it develops robust human behavior models that can be applied to study how human reasoning and actions could influence the outcome of a simulation scenario. This expands the utility of M&S from constructing strictly mechanical and mathematical models of inanimate objects to incorporating models of human behavior, which is present in various complex socio-technical systems. The DT technology has shown to be a feasible solution to model such systems, and as such, behavior modeling becomes an indispensable DT component. One DT application involving behavior modeling is the construction of an artificial society (AS), which we discuss in more detail in Section 4.

Table 1: DT capabilities and their enabling tools.

Capability	Enabling Tools
Data Visualization	Unreal Engine; Unity; R Shiny; Cesium; Apache Superset
Big Data Analytics	Apache Spark; DuckDB; RUST; Repast; Apache Superset
Distributed Simulation / Interoperability	Distributed Interactive Simulation (DIS); High Level Architecture (HLA); Kafka; ZeroMQ
Data Manipulation	Python libraries; X-Array; Apache Arrow
Behavioral Modeling	NetLogo; Experimentation Simulation Platform (ESimP); Artificial Society (with Repast and Mason)
Synthetic Population Generation/Social Networks	R; Python
Digital Twin Modeling	Simio; Exata; Cameo; One Semi-Automated Forces (OneSAF); Advanced Framework for Simulation, Integration and Modeling (AFSIM); Next Generation Threat System (NGTS); Matlab
Business Process Modeling	iGrafx

3 CURRENT DT RESEARCH AND PROJECTS

In this section, we present a few MITRE DT research projects and their associated applications in different domains.

3.1 Artificial Societies for Modeling Climate Change Adaptation

MITRE is strongly motivated in addressing the challenges presented by climate change. One project undertaken by MITRE researchers applied M&S to build capabilities to model coupled natural-socio-technical systems to evaluate options for increasing socio-economic resilience in the context of climate change. The researchers' approach was to couple climate risk data with MITRE's artificial societies (AS) simulation platform. Within the DT, the AS simulation platform (as described later in Section 4.3) provides models of populations and communities across the U.S that change over time due to population perceptions and socio-economic situations, environmental and social influences, and other selectable conditions. As a simulation platform, AS supports coupling the DTs of natural-socio-technical systems with the DTs of climate.

Artificial Society has been utilized by several research teams at MITRE who study how climate change impacts different aspects of society. In one project, the researchers studied the burden that flood insurance premiums could place on underserved communities in the U.S. Real-life climate data was fed into AS along with the data capturing flood damages to buildings given adverse weather events, such as a 1 in 100-year flood. With the aid of AS, the researchers calculated the optimal parametric insurance premium values for properties in Washington, D.C. under different flooding conditions. The researchers found that when factoring insurance premiums into the monthly cost for homeowners with a mortgage (see Figure 1), the share of income going to housing costs increases by 2.5% for households in Ward 8, and 0.6% for households in Ward 2. This illustrates the disproportionate impact that flood insurance premiums may have for Ward 8 homeowners, which already experience the highest housing burden in the District. As shown in

Figure 1, Artificial Society allows researchers to drill down to households to better understand the situation of at-risk households as well as view aggregate, community-level impacts of policy decisions.

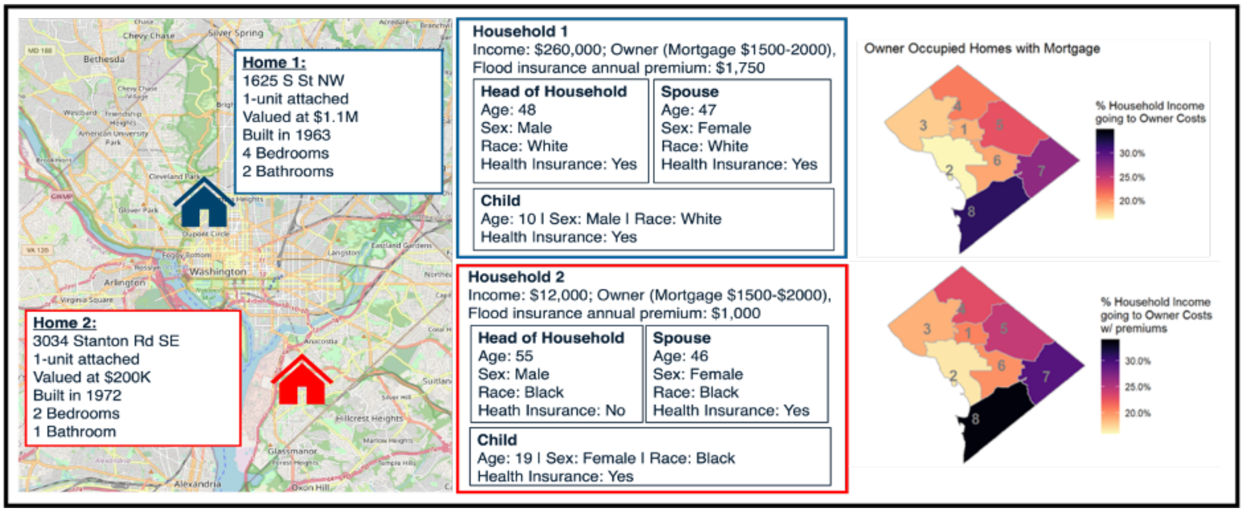

Figure 1: Household and community-level flood insurance premiums and housing costs in Washington, D.C. (Left) Two example synthetic households. (Right) Percent of household income going towards monthly housing costs for owner occupied homes, with and without flood insurance premiums, across the different Wards in Washington, D.C.

3.2 Maritime Port Digital Twins

Supply chain resilience is gaining attention in the M&S community due to its significant impact on the global economy. To better understand the role that shipping ports play in globalized supply chains, MITRE researchers carried out a study to produce a robust DT model of the Port of Mobile, Alabama. The researchers started with the 3-D rendering of the port environment using Unreal Engine, where the geographical terrain of the port was accurately captured by Cesium, a 3D geospatial platform. The port model also captured and tracked ship arrivals and departures, ship-to-shore crane movements, gantry crane movements, container handling inside of the yard and stacking, and intermodal rail. Furthermore, the researchers developed the simulation logic of port operations and integrated it into the port model.

To evaluate the port operations with the DT model, the researchers defined several performance metrics: cargo throughput, vessel turn times, vessel queue times, container dwell times, and equipment utilization. The DT User Interface, as shown in Figure 2, was developed in Unreal Engine and enabled the user to configure desired scenarios by specifying vessel and container arrival and departure frequency, as well as resource capacities (examples of such resources were the number of cranes in operation and the number of container handling machines). The DT port model also allowed the user to analyze port operations at different times and granularities. Users of the model could acquire aggregated system performance metrics across the entire time duration of interest over the entire port operation ecosystem, or they could pinpoint to specific port assets or vessels to obtain more localized metrics.

Figure 2: DT user interface components of Port of Mobile, Alabama.

3.3 A Co-simulation Framework for IoT Evaluation using Digital Twins

Vendors of Cyber Physical Systems (CPS) and IoT often need to test the performance of their devices that are situated atop their underlying infrastructure. A common approach is to test the performance of these devices individually. What is needed is the ability to test multiple devices operating simultaneously, in order to fully understand the effects of these at-scale devices working together (e.g., radio-frequency interference). By leveraging DTs, MITRE has developed an engineering methodology for IoT device evaluation and assessed its feasibility with a use case of these devices under cyberattack (Mittal et al. 2018). The researchers viewed DT engineering as consisting of three elements: modeling, simulation, and experimentation.

The methodology that the MITRE researchers developed is as follows. It starts with an IoT Model Library that holds the DTs of various IoT devices in a format that lends them to a composable scenario. These DTs follow a configuration management process that allows the usage of various instances of the DT with other relevant dependencies. The IoT Model Library also consists of virtual infrastructure models, software dependencies, and protocol adapters. These components are then composed into an IoT scenario using formalisms such as the Discrete Event System (DEVS) specification. This leads to the notion of scenario specification and provides details of the composed IoT Digital Twin. The next step formulates the notional experiments that the scenario is evaluated on. It defines the parameters that the scenarios are experimented upon, and the outcomes each experiment should end up with. Employing the DEVS formalism allows the inclusion of simulation as the enabling technology for performing experimentation. If more than one simulator is needed, the accompanying co-simulation infrastructure provides the seamless simulation capability. Once the scenario is executable and experiments available, more experiments with non-functional requirements are added in the next step. The last step brings in various other considerations such as IoT device security, safety, and IoT ecosystem considerations that may impact the overall IoT system behavior. These considerations, which are rooted in the IoT operational environment, provide relevant data that is used to calibrate the IoT device DT. Results of the calibration could be used to create more variants of the DT, which are then stored in the IoT Model Library.

To validate the proposed methodology, the researchers developed a use case in which a localized coordinated cyberattack was launched against the power grid that supported the smart thermostats in a residential building. Details of the cyberattack use case are presented in (Mittal et al. 2019), where the researchers built a DT of a Google Nest T4000ES Learning Thermostat E, an IoT-enabled thermostat, and the IoT network that consisted of four thermostat DT instances and three houses, which simulated the victims of the cyberattack; GridLab-D was used to represent the Smart Grid. The use case study demonstrated that the thermostat DT was valid, could externally interact with surrounding systems, and could display behavior that accurately reflected the current status of the IoT network (i.e., during normal operations vs. under cyberattack).

3.4 Digital Twins and Green Metrics for Sustainability Planning

Aside from product lifecycle management, smart city and urban planning are key areas of DT research and application. There is expansive literature discussing the usage of DT to model smart buildings. When designing a building, architects produce the Building Information Modeling (BIM) information, which offers a blueprint with sufficient details to describe building specifications. The BIM data readily serves as the physics-based foundation of the building DT model.

Sustainability has become a topic of immense interest among researchers of the smart city community. Many proposed solutions in the literature study the problem of sustainability planning in smart cities by looking at one green metric at a time. DTs now make it possible to take a holistic approach to enhance sustainability in smart cities by concurrently assessing multiple metrics. But different institutions have different ideas about what constitutes sustainability, and there is currently a lack of common and consistent terminology, green metrics, data, and policy across different communities and jurisdictions in the United States. This severely limits the wide adoptability of DTs in the study of sustainability planning.

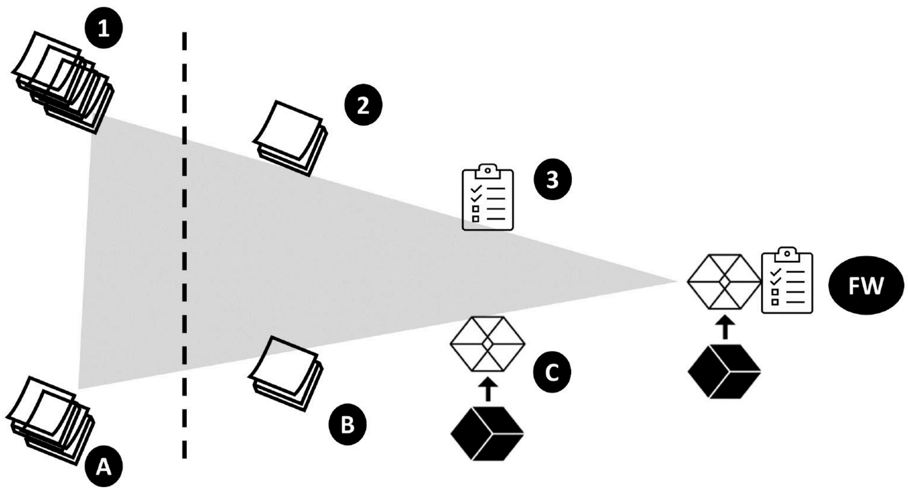

Figure 3: The methodology of developing the proposed framework.

A team of MITRE researchers have carried out extensive literature review, and developed a novel framework that leverages DTs to support sustainability planning in smart buildings and cities (Corrado et al. 2022). The proposed framework is metrics-driven, enabling computational decision support for sustainability planning. Furthermore, the researchers assert that human inhabitants are an integral part of any smart building or smart city; any sustainability planning must take into consideration the needs of inhabitants as much it considers the environment around them.

The objective of the proposed framework is to contribute to the standardization of the different concepts and terminologies while applying DTs in sustainability planning. The methodology of developing the framework is shown in Figure 3. The researchers started by conducting two literature surveys, the first on earlier studies in green metrics (1), and the second on simulation and sustainability (A). Next, among the published green metric studies, they focused on those that measured sustainability in real-life applications (2); among the studies on simulation and sustainability, they focused on DTs (B). They then identified applicable metrics (3) and applicable DTs (C). These two branches (i.e., (1)-(2)-(3) and (A)-(B)-(C)) were then merged into the proposed framework.

4 FUTURE WORK

MITRE continues to engage with academia, industry, and government to explore and develop new tools, capabilities, and use cases of DTs to support sponsor needs. In this section, we discuss three DT research directions that could generate greater value for MITRE's customers.

4.1 Digital Twin for Space Exploration

The current decade is witnessing the blossoming of many national space programs and space flight endeavors by private industry. Coincidentally, the term "Digital Twin" was first coined by NASA's John Vickers in 2009 (Grieves 2011). With great strides made in space science and technology over the past 15 years, the space domain is opening up new opportunities for leveraging DTs, and MITRE is actively engaging with the space community to explore ways in which MITRE's expertise in DTs can help address various challenges facing the community.

One of the most ambitious space exploration missions being undertaken by NASA is the Artemis Program, which is an internationally collaborative endeavor to establish a sustained human presence at the South Pole of the Moon, in a region known as the Shackleton Crater. In addition to serving as a base of operations for future lunar missions such as resource mining, the Artemis Base Camp, as this permanent human habitat is called, may also serve as a test-bed and waystation for the planned missions to Mars in the 2030s. Given its unprecedented scale and complexity, the Artemis Program has many inherent and unknown risks, which M&S, and in particular DT, could help uncover and mitigate. A paper by MITRE researchers (Hua and Boan 2023) presented the technical, social, and policy challenges the Artemis Program faced, and discussed how DTs could be leveraged to study these challenges in a holistic manner (i.e., by taking into consideration the impact of individual components on the overall Artemis Base Camp ecosystem) and provide insights on the optimal design, development, operation, and maintenance of the base camp to ensure astronaut safety and mission success.

One area of potential DT application is astronaut training. While some form of analog training for astronauts has been used by NASA since the 1960s, DTs now offer an alternative solution to capture all likely scenarios and develop well practiced solutions and procedures to improve the effectiveness of astronaut training. As illustrated in Figure 4, data captured by the sensors on the lunar surface is transmitted back to Earth, where the DT of the Artemis Base Camp is located. The DT analyzes the data and produces information that captures the daily routines and anomalies that occur on the lunar surface. It then passes this information to the training simulators, which integrate it into astronaut training scenarios, providing a more realistic environment of lunar surface conditions.

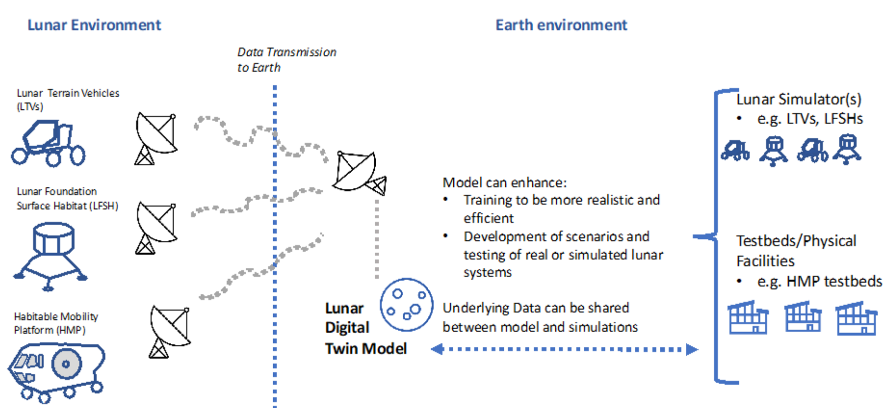

Figure 4: Digital Twin supporting astronaut training for the Artemis Base Camp (Hua and Boan 2023).

Several other exploratory studies of leveraging DTs to support U.S. Government space missions are currently being discussed and conducted at MITRE, often in partnership with academia and government agencies.

4.2 Human Digital Twin

The last few years have seen a robust growth of DT research leading to an expanding list of applications in different industries and sectors from its origin in PLM. Most of the DTs mirror the state and behavior of inanimate entities, whose actions and reactions are solely governed by the laws of physics. A nascent research topic that is gaining increasing interest is the Human Digital Twin (HDT). The physical entity in HDT is organic matter, which even at a very simple form, may be seen as a dynamic, complex system of systems. While an end goal of HDT is to create a full-body person DT, researchers have been making inroads creating DT models of cells, organs, and limbs. Applications of HDT can be found in healthcare, workplace safety and wellbeing, combat casualty care, military training and exercise, smart construction, and crewed space flight, among others.

Depending on its usage, a robust HDT requires the modeling of at least one or both of two principal dimensions: physiological and psychological. Davila-Gonzalez and Martin (2024) presented a HDT for the study of enhancing human health and safety at work. Their HDT model consisted of three principal components: physical body (i.e., physiological), mental domain, and emotional status (i.e., psychological). The physiological modeling of a human body is relatively straightforward to capture and model (e.g., with smart watches, Fitbits, IoT sensors, etc.). The psychological modeling of a human mind (behavioral and emotional), on the other hand, is substantially more difficult. Although behavior models have been developed for various use cases over the years, the accuracy of such models is not sufficient. This remains an open problem to be resolved before a robust, actionable HDT can be successfully developed.

MITRE Researchers have conducted preliminary studies of HDT that could support future government programs. They produced a paper (Byrne et al. 2023) that drew on the lessons learned in the defense simulation domain, and presented the concept of operations, services, and metadata specifications for a modeling capability that could simulate a soldier's injury, lethality, and impairment caused by blasts on the battlefield. The researchers asserted that such a modeling capability would require establishing technical connectivity, data alignment, and logical consistency between all the participating models and simulations. Moreover, they discussed the challenges of simulation interoperability, including 1) interdependence between scope, resolution, and structure of data in human body modeling; 2) verification and validation (V&V) of the models; 3) knowledge gaps that may exist as a result of, for example, not understanding the underlying mechanism that caused a particular injury. These challenges, in fact, are all present in the HDT modeling that need be addressed. Without explicitly resolving these challenges, the researchers described a concept of operations of applying such a modeling capability. This work could be used as a precursor towards developing a HDT for wounded soldiers on the battlefield.

4.3 Artificial Societies Modeling as a Platform

The Artificial Society is a computer simulation (DT) of real-world, dynamic communities. It was developed to help policy makers think about second and third order effects of policies and interventions in the context of the socioeconomic situation, behaviors, and social networks of individuals affected by policy decisions. As shown in Figure 5, an Artificial Society consists of the following three important elements:

- Individuals are represented as software agents who can perceive their environment, communicate with other agents in their social and interaction networks, and make decisions influenced by their belief system, networks, and socioeconomic situation.
- The situated environment constrains and enables the movements and actions of agents. It provides access to resources, workplaces, schools, places of worship, and more. It can also impact agents' social determinants of health, such as access to healthcare, safe drinking water, air-conditioned spaces, and tree coverage.

- Finally, social networks interconnect the agents (e.g., friends, colleagues, family). Information flows and exchanges can occur through these networks, potentially influencing the decisions, opinions, and beliefs of agents.

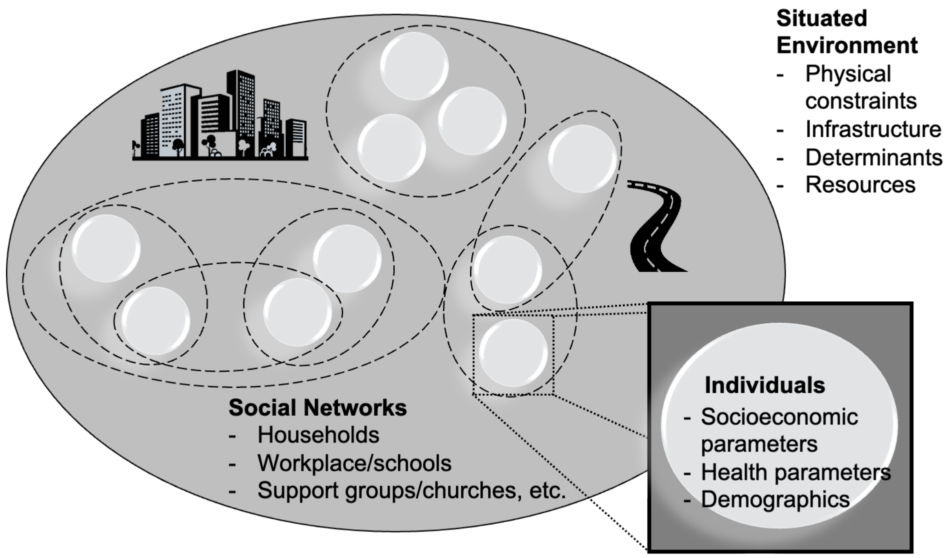

Figure 5: Elements of an Artificial Society (Tolk et al. 2022).

The Artificial Society was developed using a suite of open-source tools, enabling scalability and reusability across a variety of geographies, applications, and domains. Figure 6 provides a high-level depiction of the integrative and layered approach: 1) a data layer incorporates a variety of data types and is developed using Apache's suite of software (Arrow, Druid, Kafka), enabling high-performance data computation, storage, and transport; 2) a dynamic, spatially explicit simulation engine built with Repast HPC and Repast for Python enables large-scale, high-resolution, distributed computing; and 3) an evaluation layer with a user-friendly interactive dashboard built upon Quarto and Apache Superset and orchestrated by Kubernetes allows for scenario analysis, data exploration, and data visualization. Integration of the three layers is possible by applying a data science workflow that supports agile and collaborative development (https://drivendata.github.io/cookiecutter-data-science/). While the details of the individual layers may vary depending on the particular use case, the process for generating, the methodologies applied, and many of the data sources used for creating the layers is largely reusable across application areas and domains. Examples of use cases developed include the opioid epidemic in Washington, D.C. (Tolk et al. 2024), the financial burden of flood and wildfire insurance premiums on vulnerable residents of Washington, D.C. and Boulder, Colorado, respectively (see Section 3.1), and the impact on port operations and military readiness after a major flooding event in southeast Texas.

An important consideration throughout the AS development has been to reduce the barriers to entry for future modelers, users of the platform, and policy makers. Current and future work centers around providing tools for generating agent populations, communities, and behaviors in intuitive, well-known scripting languages such as R and Python. Towards that goal, multiple, parallel research efforts are currently underway. These include:

- A standardized behavioral engine for integrating the varied components of human behavior within a distributed simulation architecture.
- A synthetic population generation capability for creating up-to-date, statically representative populations of communities across the country and their movement. For health use cases, the population may be further integrated with Sythea™ (Walonoski et al. 2018), a synthetic patient record generator.

- The generation of social networks given known demographics and affiliations of the population that adheres to aggregate, known properties of real-world social networks.
- Calibration and uncertainty quantification of simulation runs using methods such as Approximate Bayesian Computation and Gaussian Process emulators (Baker et al. 2022).

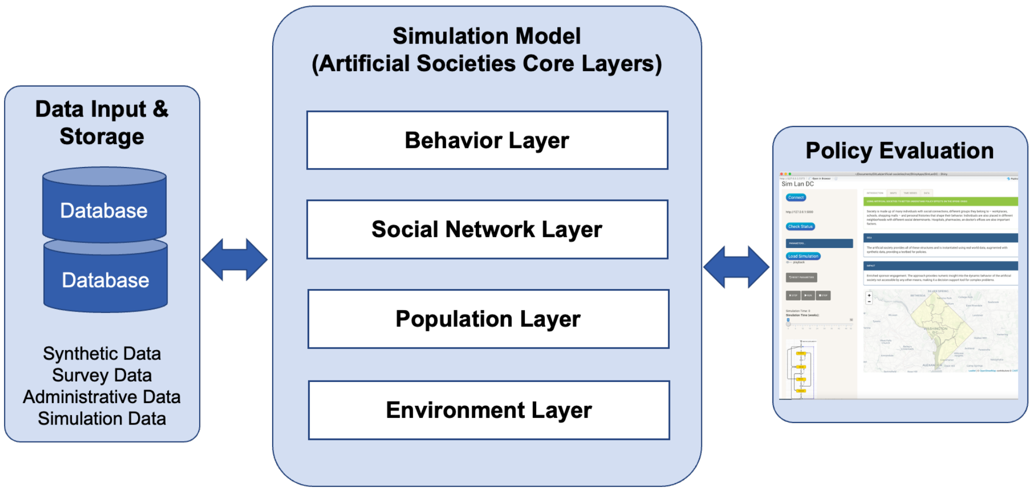

Figure 6: An integrative layered approach to building an Artificial Society.

5 CONCLUSION

A growing recognition of the importance of digital transformation across all echelons of the U.S. government has led to a renewed interest in applying digital technologies to help resolve some of the most pressing challenges facing the Nation. DT engineering brings value to many of the government programs supported by MITRE. As a FFRDC, MITRE is actively working to identify capabilities, tools, and application use cases related to DTs to support its government customers' mission needs. Through directly funded projects and independent research, MITRE researchers have been developing DT-related capabilities in areas such as modeling and simulation, data visualization, big data analytics, and behavior modeling.

This paper showcased several projects that MITRE is pursuing using these developed DT capabilities. The presented projects focused on four different applications: climate change adaptation, maritime port operations, performance evaluation of IoT devices, and smart city and sustainability planning. A common theme of these different projects is to use DT to explore the different configurations in each application, and to choose the best one that meets the performance criteria.

We have identified three areas with strong future growth potential as areas of future research that MITRE should undertake. These are DT engineering in space exploration, Human DT engineering, and Artificial Society DT engineering. We believe these areas will bring greater value to MITRE government customers.

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AUTHOR BIOGRAPHIES

EDWARD Y. HUA is a Lead Modeling & Simulation Engineer at the MITRE Corporation. He received his Ph.D. degree from Cornell University, a Master of Engineering degree from Princeton University, and a Bachelor of Science degree from University of California, Irvine, all in Electrical and Computer Engineering. He is a member of ACM SIGSIM and INFORMS. His research interests include digital twins, simulation and AI, and wireless networks. His email address is ehua@mitre.org, and his website is https://www.linkedin.com/in/edward-hua-ph-d-1296025/. His ORC ID is 0000-0002-6294-3122.

JON CLINE is a Lead Modeling & Simulation Engineer at the MITRE Corporation. He holds a PhD in Ecology & Evolutionary Biology from Princeton University, and a M.S. in Operations Research and a B.S. in Computational Mathematics from Stanford University. Before joining MITRE, he was an assistant research professor at the University of Tennessee, a Research Associate and High-Performance Computing Cluster Administrator with Case Western Reserve University, and a Postdoctoral Research Associate at the University of Arizona. He published on the computational modeling in support of ecological challenges and recently supported multiple government organizations with his work on complex adaptive systems. His email address is jcline@mitre.org.

ROBERT WITTMAN is Senior Principal Modeling & Simulation Engineer and Department Manager at the MITRE Corporation where he leads an organization performing simulation, experimentation, and gaming across MITRE's sponsors. He actively develops and uses a variety of military simulations and associated tools for work across the experimentation, analysis, and training domains. He holds a PhD in Simulation from the University of Central Florida, a M.S. in Software Engineering from the University of West Florida, and a B.S. in Computer Sciece from Washington State University. His email address is rwittman@mitre.org.

BIANICA PIRES is a Principal Modeling & Simulation Engineer at the MITRE Corporation. She is a computational social scientist by training and experienced in developing computational models of complex social systems. Prior to joining MITRE, she was a Research Assistant Professor at the Biocomplexity Institute of Virginia Tech. Dr. Pires received her Ph.D. in Computational Social Science from George Mason University, and her M.A. in International Business and her B.S. in Industrial & Systems Engineering from the University of Florida. Her email address is bpires@mitre.org.