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Abstract

Framework Incorporating Complex Uncertain Systems (FICUS) provides geographic risk analysis capabilities that will dramatically improve military intelligence in locations with the Engineer Research and Development's (ERDC) demographic and infrastructure models built and calibrated. When completed, FICUS would improve intelligence products by incorporating existing tools from the National Geospatial Intelligence Agency, ERDC, and FICUS prototype models, even in places without demographic or infrastructure capabilities. FICUS would support higher-fidelity intelligence analysis of population, environmental, and infrastructure interaction in areas with Human Infrastructure System Assessment (HISA) and urban security models built and calibrated. This technical report will demonstrate FICUS prototype tools that allow Civil Affairs Soldiers to provide situational awareness information via a browser interface.

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Preface

This study was conducted for Headquarters, US Army Corps of Engineers, under Research, Development, Test, and Evaluation (RDT&E) Program Element 0603734A, "Military Engineering Advanced Technology"; Project T08, "Human Geography Demonstration." The technical monitor was Ritchie L. Rodebaugh, US Army Engineer Research and Development Center, Geospatial Research Laboratory (ERDC-GRL).

The work was performed by the Emergency and Operational Support Branch of the Operational Science and Engineering Division, US Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). At the time of publication, Ms. Ellen Hartman was branch chief, Dr. George Calfas was division chief, and Mr. Jim Allen was the technical director for Operational Science and Engineering. The deputy director of ERDC-CERL was Ms. Michelle Hanson, and the director was Dr. Andrew Nelson.

The work was also performed by the Environmental Risk Assessment Branch of the Environmental Processes and Engineering Division, US Army Engineer Research and Development Center, Environmental Laboratory (ERDC-EL). At the time of publication, Mr. James Lindsay was branch chief, and Mr. Warren Lorentz was division chief. The deputy director of ERDC-EL was Dr. Brandon Lafferty, and the director was Dr. Edmond J. Russo Jr.

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Fort Collins, CO, edited by Mazdak Arabi, Olaf David, Jack Carlson, and Daniel P. Ames (Provo, UT: International Environmental Modelling and Software Society, 2018), 9, https://scholarsarchive.byu.edu/iemssconference/2018/Stream-F/9.

COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

Executive Summary

The Framework Incorporating Complex Uncertain Systems (FICUS) provides geographic temporal risk analysis capabilities that will dramatically improve military intelligence (MI) in locations with Engineer Research and Development's (ERDC) Human-Infrastructure System Assessment (HISA) and urban security models built and calibrated. With another year of development, FICUS tools could provide resilience monitoring, with comprehensive geographic and temporal risk analysis, which would improve intelligence products by incorporating existing tools from National Geospatial Intelligence Agency (NGA), ERDC, and FICUS prototype models: even in places without HISA or urban security capabilities. FICUS would support higher-fidelity intelligence analysis of population, environmental, and infrastructure interaction.

Over recent decades, significant, complex emergencies around the world occurred in densely populated urban areas. While many technological solutions offer some understanding of today's complex multidimensional urban terrains, more work must be done to model the human system within the context of urban physical systems. FICUS fills this informational gap by systematically combining multiple sources of human data and surveys, already routinely collected, to provide a population representation containing the interrelationships necessary to analyze and forecast complex human behavior.

FICUS has the capability to combine disparate surveys and data sources, such as household information, with digital networks of infrastructure systems to generate a range of potential scenarios given various courses of action. FICUS provides decision makers, the worst- and best-case scenarios at higher resolutions and fidelities far better than previously thought possible, thereby dramatically improving the ability of combatant or base commanders to calculate and manage risks in urban operations.

FICUS computationally handles the complex overlap of the physical, human, and information systems within and around populated areas to allow planners, analysts, and operators the ability to track, monitor, and gauge how human-physical system connections impact military operations. Conversely, FICUS also provides decision makers the second- and third-degree order effects of various military decisions and courses of actions in dense urban environments as well as rural and smaller cities. Essentially, FICUS

serves as a critical complementary analytical tool for any type of qualitative analysis that could benefit from the intelligence derived from leveraging large disparate data sets.

1   Introduction

Human Geography Demonstration (HGDemo), a one-year Engineer Research and Development Center (ERDC) development effort, contains multiple complex analysis capabilities and an integrating computational framework: Framework Incorporating Complex Uncertain Systems (FICUS). FICUS supports all the functions of a general purpose geographic and temporal analysis system with a focus on risk analysis. Capabilities supporting intelligence operations include population vulnerability, transport networks in conflict zones, and analytic frameworks. We use the term "general purpose (system)" to indicate that FICUS is designed to help answer complex spatial and temporal problems regardless of the specific application, especially when the various data are "fuzzy" or contain highly uncertain information.

1.1   Background

Currently, Soldiers performing intelligence preparation of the battlefield (IPB) mostly use authoritative very accurate information that is also precise, both spatially and temporally, enough to be operationally useful. Current practices discourage less precise or more dynamic data. IPB-performing Soldiers rely on analysis frameworks composed of data collected by the intelligence community and higher echelon units. The information in this framework is currently static and does not change even though operations will change the operational environment, especially during large natural disasters and significant conflicts. Even when IPB-performing Soldiers have access to up-to-the-minute data, they lack the tools to modify the analysis framework to keep it up to date.

1.2   Objective

FICUS alleviates both of the IPB problems. FICUS encourages the inclusion of accurate but not precise data by providing a visualization environment that demonstrates the utility of the nonprecise data in the IPB maps themselves. Soldiers need not understand the certainty of each data layer as the maps they desire visually represent all sources of information uncertainty intuitively presented. FICUS also ingests complex models supporting IPB, allowing Soldiers to compare different courses of action by

providing them with straightforward mechanisms to input ground truth information that will only be available to the units in the operations.

1.3 Approach

FICUS embraces all five principles outlined in the *Army Data Strategy* (Army CIO-G6 2016): **visibility**, **accessibility**, **understandability**, **trustworthiness**, and **interoperability**. The FICUS user interface (FI-CUS-UI) enhances traditional Army spatial-data-sharing techniques by providing a web-based, spatial-temporal mapping environment that is nearly as easy to use as Google Earth (*Army Data Strategy*'s **visibility**, **accessibility**, and **understandability**). It uses animation to represent uncertainty and temporal information dynamics so that Soldiers can quickly determine if the available information and models are suitable to their mission (*Army Data Strategy*'s **trustworthiness**). The FICUS-UI uses the Object Modeling System to allow interoperability with software models useful to mission planning and execution (*Army Data Strategy*'s **interoperability**).

1.4 Scope

HGDemo integrated multiple ERDC capabilities within FICUS to demonstrate enhanced Human Domain analysis: a disease model, a population analysis model, and an infrastructure system-of-systems model.

1.4.1 Understanding disease in conflict zones

Over three billion people live in a country in which health risk from mosquito-borne diseases are endemic (Dahmana and Mediannokov 2020). With changing temperatures and increased extreme weather events, the global reach of these diseases is expanding. Current civil-military operations (CMO) practices do not possess the capability to predict the when, where, and effect of these mosquito-borne diseases. They, therefore, do not have the best situational awareness as to which preventative techniques to use, whom to vaccinate, medical supplies needed, or critical areas in which civilians should be given greater protection. Additionally, without understanding how a disease will spread, Soldiers could potentially be unable to protect themselves from these predictable health risks, directly affecting mission readiness and effectiveness. As seen in the West African Ebola epidemic that occurred between 2013 and 2016, infectious disease can severely disrupt not only the public health of a region, but also

its social and economic stability. With the increasing spatial distribution of mosquito-borne diseases and the growing resistance of these diseases to medicines, it is imperative that future CMOs incorporate a robust understanding of when and where these diseases can occur and spread, their severity, and how CMOs can alter those potential outcomes.

Efforts typically used to map and predict the spread of many vector-borne diseases tend to focus on either the environmental parameters of a study area or its sociocultural characteristics. Vector and reservoir habitat mapping and network epidemiology use both environmental and sociocultural data to map and predict the threat or prevalence of febrile and vector-borne infections (FVBI). However, these two methods are rarely studied in conjunction and assume static conditions, leaving them unable to account for rapid urbanization and ecological effects on vector populations. Changes in temperatures extend breeding seasons, providing more time for disease transmission. Modern global transit enabled Zika, a disease primarily found in Africa and Asia, to cross oceans and spread across Central and South America. As population booms outpace infrastructure developments, the rise in open-water storage increases the availability of breeding habits for mosquitoes. The interplay between environmental parameters and sociocultural dynamics must be considered together to combat FVBI in both rural and urban settings.

These factors are amplified in potential situations of conflict or natural disaster. The destruction of terrain, disabling of physical infrastructure, and forced displacement of local populations place a region more at risk for disease outbreak. Further, in situations of crisis and conflict, resources designed for vector-borne disease control are often redirected to more urgent issues. These factors are of paramount consideration when planning civil-military operations, such as troop deployment, temporary rehoming of displaced persons, and infrastructure redevelopment. Further, with vector-borne diseases, standard mechanisms of quarantine are more difficult, and terrain degradation can result in the spread of habitable areas for vectors. To be able to make decisions with full situational awareness, understanding the outbreak potential of a region is paramount. While the FVBI model discussed here does not represent COVID-19 impacts, COVID-19 models could be incorporated easily and quickly.

1.4.2 Population analysis in conflict zones

FICUS's population dynamics modeling environment provides Soldiers with combat situation awareness to quickly understand dynamic situations such as refugees due to damaged infrastructure; nuclear, biological, chemical (NBC), and other combat conditions. Section 2.5.2 demonstrates the combination of demographic and visualization capabilities to examine the potential impacts of the Battle of Marawi, May–Oct 2017, on population in Mindanao, Philippines. The Battle of Marawi is often considered an outlier due to the large number of internally displaced people. However, we chose that battle because of the large amount of open-source data available. Smaller and more frequent conflicts would employ similar techniques, but the impacts would likely be only known by the Soldiers and the headquarters of the units assigned to the conflict region. Our population modeling capabilities are designed to be general purpose, allowing any result, but our refugee model classifies population into four different groups, or cohorts, of people: those fleeing the conflict to family or friends, those that are sheltering in place, people forced into refugee camps, or casualties. Soldiers can use their domain knowledge of the specific conflict to identify the factors that will probabilistically define which of the four specific types people will end up in. For example, What is the likelihood that "non-Muslim adult males" from the combat zone will become casualties? This technique combines traditional demographic analysis, geographic information analysis, and uncertainty quantification in a user-friendly editing environment to allow Soldiers to incorporate vague or uncertain information in their analyses.

1.4.3 Infrastructure system of systems

FICUS incorporates and improves on earlier ERDC research in system of infrastructure modeling under the program Human-Infrastructure System Assessment (HISA) (Wang et al. 2016). HISA estimates the cascading physical damage on infrastructure components (e.g., electric generators, freshwater storage tanks, and bridges) and determines how the change in available infrastructure impacts at a neighborhood scale. When the local resources are not available to the people in the neighborhood, the agent-based model will calculate the additional trips necessary for resources to be collected, further stressing the transportation network. The HISA model was augmented in the HGDemo Program to allow Soldiers to quickly and intuitively mark the locations of broken infrastructure using

the web-based application and run HISA from either their local computer
or an application server.

2 Human Geography Demonstration (HGDemo) Products

2.1 Visualizing uncertainty and risk assessment

The FICUS framework analysis uses a stochastic simulation approach to generate uncertainty quantification (UQ) maps at each level of the framework. This supports an overall assessment measure while simultaneously enabling analysts to look at data at any point within the analysis process to examine the effects of each individual framework component. For example, if the assessment of access to medical care was in question, subordinate maps are available to express the nature of the facilities and services separately. This allows the analyst to potentially adjust the framework elements or weighting values if it is suspected the results are in error. The analysis process can include maps (such as weighted distance to facilities) that do not have explicit uncertainty; thus, UQ data and static data can be fully incorporated in the analysis. The maps are available to be viewed in a web-based visualization tool that can show static maps, animations of the variation in results, or the uncertainty of results as measured at specific points. This research is described in detail in Ehlschlaeger, Browne, et al. (2016).

This section describes the FICUS-UI, focusing on elements that provide quick communication of difficult-to-discuss–spatial-temporal analyses (Figure 1).

Figure 1. Framework Incorporating Complex Uncertain Systems—user interface (FICUS-UI) home page.
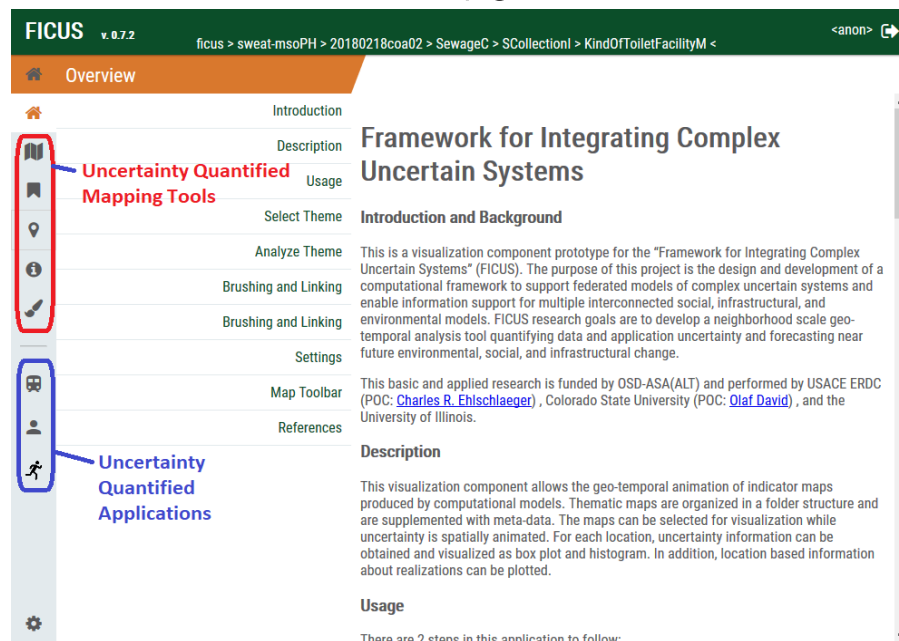
2.1.1 FICUS-UI overview

The FICUS-UI provides for a data set containing terabytes of map data to be on a map server runnable on laptops, desktops, DoD servers, and cloud services. Computers running Windows 10 Pro, LINUX, and Mac OS can run the FICUS-UI. Whether available to a local area network, a single computer, or the entire internet, the FICUS-UI makes the maps and supporting data available in any number of web browser windows, either on one computer or many computers simultaneously.

2.1.2 Viewing and selecting themes

Thematic maps in the FICUS-UI are organized in a folder structure and the themes are supplemented with metadata. These are visible to the left of the map panel. The organizational structure makes it easy to publish analytic frameworks. Figure 2 shows how the SWEAT-MSO framework would be presented in the FICUS-UI. (The SWEAT-MSO framework organizes information into the military engineering categories: **s**ewage, **w**ater, **e**lectricity, **a**cademics, **t**rash, **m**edical, **s**afety, and **o**thers).

Figure 2. FICUS mapping with selecting themes in analysis framework.
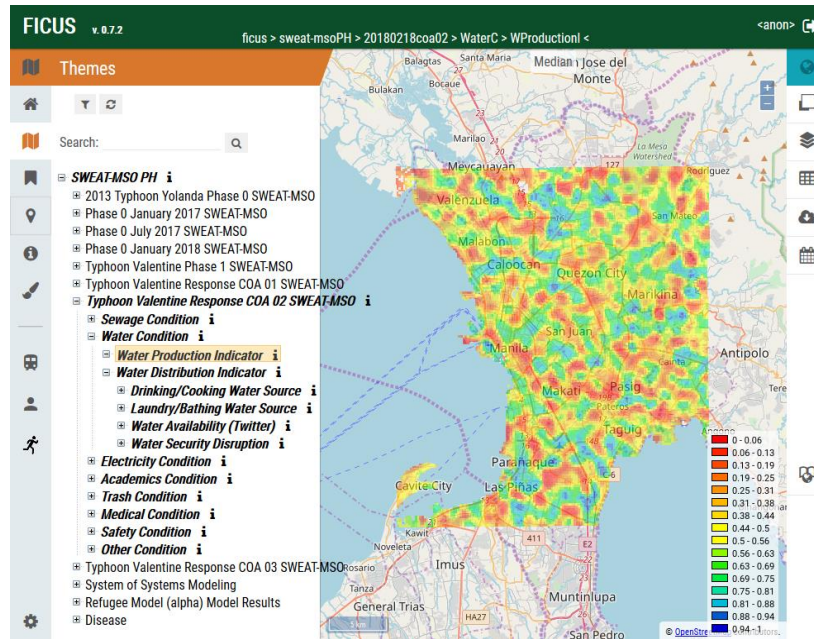
We envision analytic frameworks in a time series from recent to present to forecasted. Subcategories of framework indicators are presented as sub-sections visible by clicking on the + buttons to the left of the category name. As shown in Figure 2, the **Water Condition** has two indicators: **Water Production Indicator** and **Water Distribution Indicator**. And the **Water Distribution Indicator** has multiple metrics, including **Cooking/Drinking Water Source** from the Philippine Census Micro-data. A more complete description of organizing quantitative analytic frameworks can be found in Ehlschlaeger, Browne, et al. 2016.

The FICUS-UI will remember the themes viewed in the Bookmarks/History button on the far-left column. Important or often used themes can be bookmarked to access recently used or important themes (Figure 3). Users can download a text file containing all bookmarked themes. The FICUS-UI will then allow a user to open all the themes in the bookmarked text file in separate tabs on the same browser window, whether on the same computer or, if the file is mailed to colleagues, on any computer that can access the FICUS server.

Figure 3. FICUS history and bookmarking capabilities.
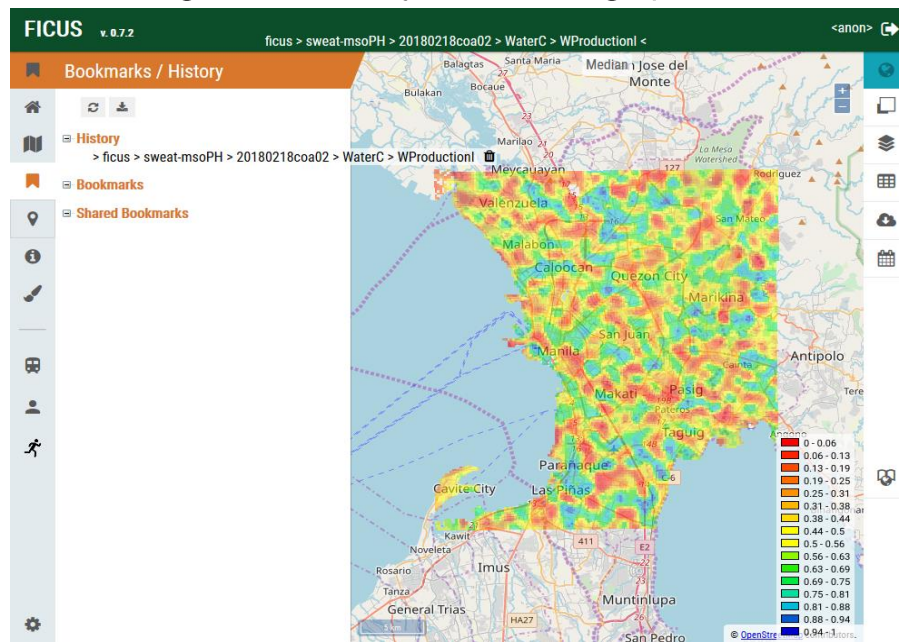
2.1.3 Viewing theme uncertainty

The FICU-UI demonstrates novel visualization techniques to communicate uncertainty. We cannot expect users to have mastery of advanced statistical techniques or novel visualization tools, so communicating uncertainty requires that the FICUS-UI be able to demonstrate thematic uncertainty in intuitive ways. The FICUS-UI presents uncertainty in four ways:

1. A distribution of possible thematic values in **Summary Maps**,
2. A **Multiverse of Maps** showing the varying possible thematic maps,
3. **Popup Distribution Windows** showing the distribution of possible theme values at chosen locations, and
4. a **Gray Swan Chart** analysis tool of the thematic maps' multiverse.

Ideally, each realization map in the multiverse is composed of techniques accounting for known errors and uncertainties of source data. For socio-cultural analyses, dozens of metric maps are fully quantified for uncertainty due to techniques from Ehlschlaeger, Gao, et al. (2016), which are demonstrated in the applications later in this technical report.

Summary Maps are a set of maps that present the range of possible theme values in map form (Figure 4). When selecting the Quartile Tab in the Analysis Display, the FICUS-UI map server will display the maps in the following order two seconds apart: minimum value for all realizations,

first quartile value for all realizations, median value for all realizations, third quartile value for all realizations, and highest value for all realizations. When a user is looking at a section of the map, how often the topology of the map changes shape for an object-based map or how often the colors that represent the theme's value change (or both) communicate uncertainty. Maps with large extremes between best case and worse case situations indicate the source data and model variability is too great to get an accurate and precise representation of the desired information. While **Summary Maps** provide the quickest way to interpret uncertainty, the pattern of the theme's values ends up being generalized, thus losing spatial fidelity. In addition to the quartile maps, users can look at maps showing the average values, standard deviation, range, and interquartile range maps in the Others tab.

Figure 4. FICUS presenting uncertainty summary statistics.
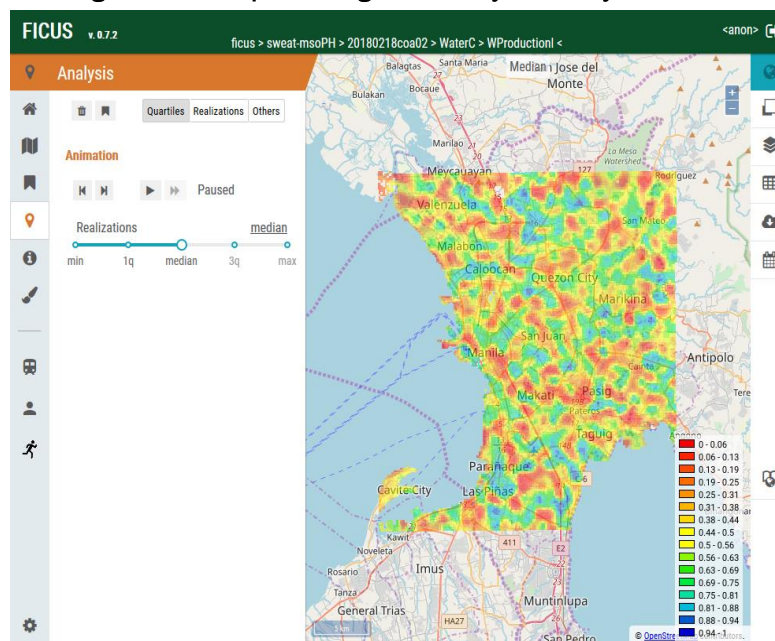
As with both **Summary Maps** and the **Multiverse of Maps**, users can choose to stop or start the animation, select which maps to look at, or speed up and slow down the animation speed.

The **Multiverse of Maps** represents all the realizations of a theme. FICUS uses Monte Carlo simulation to represent uncertainty, which is the only way accurate representations of reality can exist, including cross-attribute correlations as well as spatial and temporal patterns. To observe these high-fidelity representations, animating the multiverse across all

realizations is required (Ehlschlaeger et al. 1997). FICUS-UI allows the users to see these relationships when clicking on the Realizations tab. Users can view the multiverse realizations via animation in four different patterns:

1. The "Default" mode views the multiverse randomly by animating realizations in a loop in order by realization number, as shown in Figure 5.
2. The realizations can be viewed with "gray swan" ordering based on all the map values (described below).
3. The realizations can be viewed with gray swan ordering for the map values at a single location.
4. The realizations can be viewed in an order determined by the "Values at [a specific map] location."

Figure 5. Theme realization values at a location with a popup distribution window.
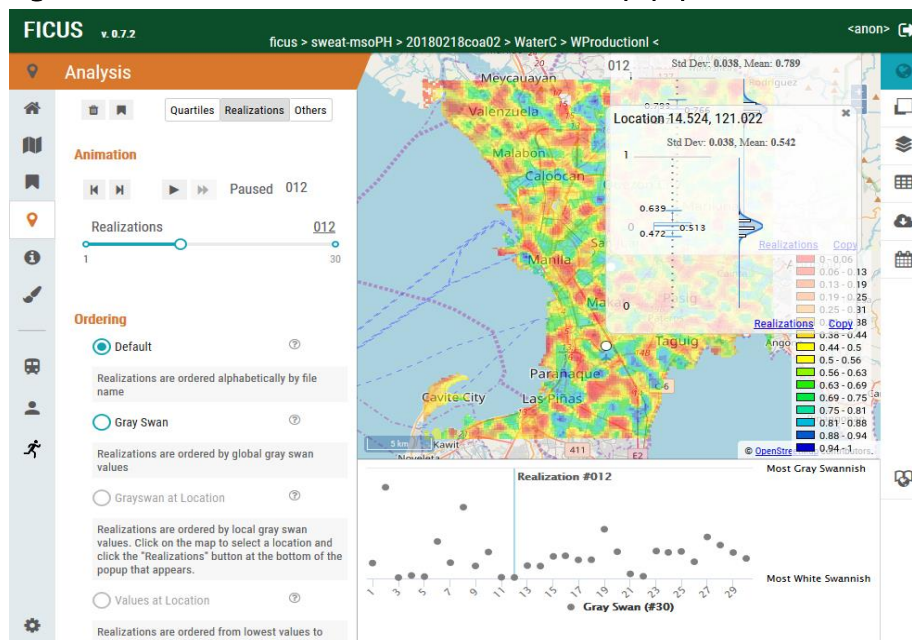
Popup distribution windows shows thematic map values at user chosen locations (Figure 5). The possible range of values are represented both as a histogram of values as well as a statistical curve.

The **Gray Swan Chart** pops up at the bottom of the window whenever black swan theory capabilities are used, as shown in Figure 6. Gray swan order has the realizations reverse ordered on how closely the map layer is similar to the median values of that theme. Gray swan ordering aids planners and decision makers by quickly allowing them to see extreme examples in the multiverse: also known as best-case and worse-case situations.

Depending on the theme represented and the situation at the time, high values or low values will be best-case or worse-case situations. When in Gray Swan mode, users can select median results by clicking on the realization maps at right-hand side of the Gray Swan Chart. They can view more extreme results by clicking on the realization maps at the left-hand side of the Gray Swan Chart. When animating through the multiverse, users will see more extreme results first, also known as the gray swan events based on model results, with more "white swannish" results afterwards.

Figure 6. Multiverse of maps with Gray Swan Chart.
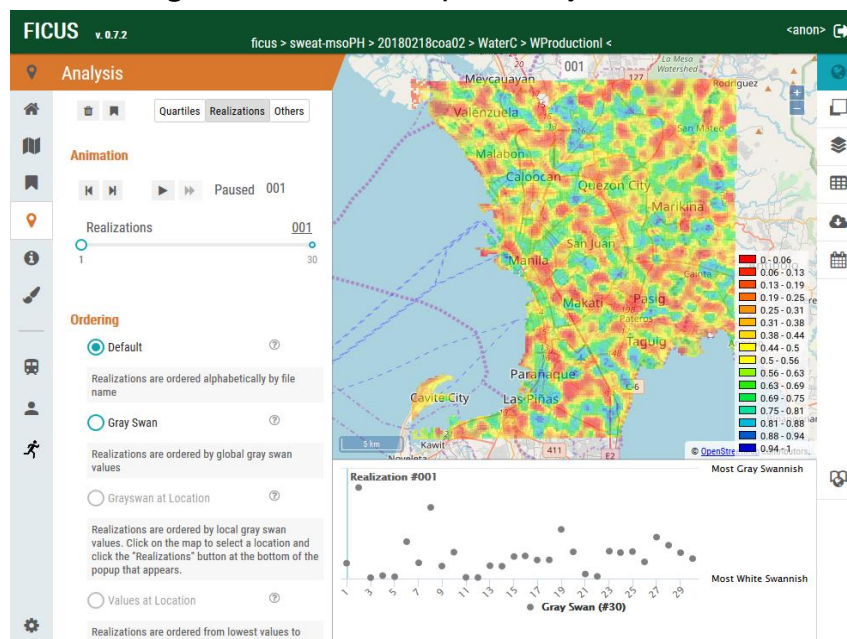
The FICUS-UI can also gray swan order realizations based on specific locations of a map theme. Figure 5 shows the summary statistics of a map layer at a user-selected location. When location summary statistic windows are open, the Gray Swan at Location option becomes available. When chosen, the realizations will be ordered by the values most different from the average map theme value at that location. Ehlschlaeger (2018) proposed a "Quantitative Black Swan Theory" allowing spatiotemporal analyses to calibrated and validated against ground truth data by defining model results as "more white swannish" or "more gray swannish." Black swan theory describes "black swan events" as those events impossible to be forecast from our, or our models', perception of reality. Thus, any model results can only be white swans or gray swans, which the FICUS-UI can arrange from the "most white swannish" (most expectable) model result to the "most gray swannish" (least expectable). The range of model results

goes from the most optimistic gray-swannish model results to the expected white swannish, to the most pessimistic gray-swannish results. The quantitative black swan theory taxonomy provides a better foundation for communicating the quality of models, measuring their utility for representing the real world using indicators and metrics important to planners and decision makers. Locations in the map can be selected to see statistics for all realization values at that point.

2.1.4 FICUS-UI multiuser, multisite visualization capabilities

The FICUS-UI is designed to facilitate collaboration between users at different locations. Multisite collaboration is especially important when data collectors, information analysts, analytic framework developers, and decision makers belong to different organizations. Data collectors useful to the DoD are located throughout the United States Government (USG), from satellite-oriented agencies like NASA, survey businesses such as Gallop, Intelligence Soldiers at command staffs, intelligence agencies such as the Defense Intelligence Agency, and most importantly, Soldiers and other USG personnel in the field. Information analysts convert raw data into useful data streams, including thematic maps, time series data, and time series thematic maps, which the FICUS-UI is capable of presenting with animation. Information analysts are located throughout the USG, from open-source agencies like NASA, command staffs, intelligence agencies, combatant commands, and private companies contracting for the DoD. Most of these information analysts *never* directly communicate with analytic framework developers and decision makers, so the trustworthiness of these data streams is difficult to interpret using current operational capabilities. The FICUS map server and user interface is designed to facilitate better communication of complex spatial and temporal information.

The FICUS map and data server maintains a database that can be viewed by anyone with network access. Normally, how a user navigates the map window to is not known to other users. However, a user can share map navigation details with other server users with the **Share/Join** feature within the **Brushing and Linking** tab (Figure 7). When a user creates a shared session, anyone with access to the map server can have some or all their map windows join that shared session. All FICUS-UI map windows in a shared session will pan, zoom, map animate, and have location charts in sync with all other map windows in the session. Since users can have many maps open simultaneously, a group of users can real-time share much more information than any teleconference. Because map animations

are calculated locally, the FICUS map server can reasonably deliver map content to users with as little as a 4G connection. Thus, all content creators and users can collaborate in real time, from battlefield staff offices to all USG organizations around the world. For example, battlefield or disaster-relief decision makers could immediately circle together data collectors and information analysts with the Soldiers performing intelligence preparation of the battlefield so that they can determine the trustworthiness of maps for that day's and week's command decisions.

Users can choose which of their map windows will be part of a session and whether that map window will cause other windows to pan, zoom, and automatically cause changes to the animation modes. The **Observer Mode** switch toggles whether that map window affects other map windows of the same session. This version of the FICUS map server does not allow users to see other users' open maps. However, the FICUS-UI lets a user create an ASCII text file listing their open maps' URLs, which can be emailed or chatted to the collaborators. Collaborators with access to the FICUS map server can use the URLs to open those maps in their own windows.

Figure 7. Multiuser real-time collaboration setup.
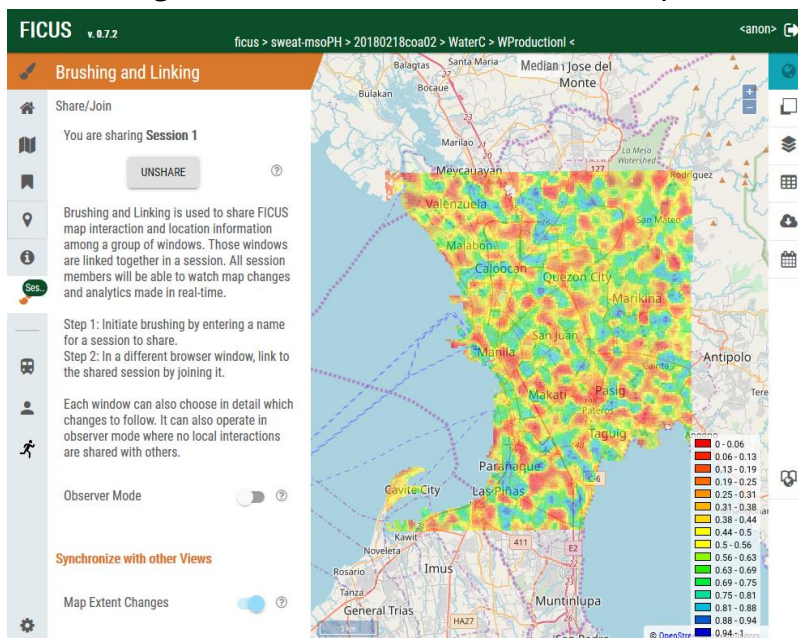
2.1.5 FICUS-UI multithematic visualization capabilities

The **Share/Join** feature within the **Brushing and Linking** tab, described in 2.1.4, also allows a single user to perform cartographic visualization on many themes simultaneously. By creating a named session, a user

can link multiple maps together. It is best to initiate this process in a single browser window with a map in each tab. After getting all tabbed maps shared, the user can move each tabbed map to their own window ensuring all windows have identical sizes and will present all maps identically, as shown in Figure 8. The brushing and linking capabilities are achieved by map change requests to the FICUS map server; resizing a browser map window currently does not send that information to the FICUS map server.

Figure 8. Multitheme "Link and Brushing."
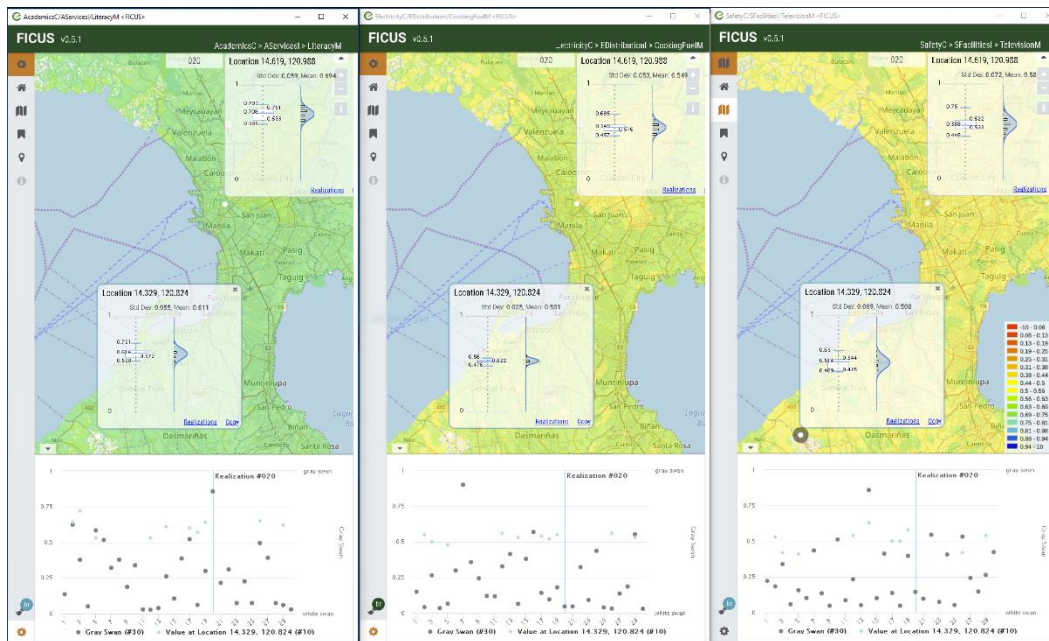
Normally, it is difficult to easily see multiple themes that completely cover a study area in a single map because varying colors is the most intuitive cartographic technique. While colors can be mixed or combined with symbols or textures to represent multiple themes, it is far simpler for noncartographers to see a single area-covering theme per map. A single theme per map can be augmented with symbols to geographically locate the desired information in each theme. Seeing multiple themes is especially useful when analyzing analysis framework layers.

Figure 9 demonstrates how the FICUS-UI uses the popular collapsible tree diagram technique to present how dozens of thematic map layers can be combined to create a spatial analysis framework, specifically SWEAT-MSO.

Whether SWEAT-MSO or political, military, economic, social, infor-
mation, and infrastructure (PMESII), analysis frameworks organize criti-
cal decision-making information, enabling large organizations to integrate
the necessary data streams. Typical analysis frameworks for US Army
commands contain dozens of maps and supporting documents, often hun-
dreds of pages, tailor suited to specific missions and commander prefer-
ences. Current practices have geospatial analyses performed by
Intelligence Soldiers preparing cartographic maps for the analysis frame-
work. These maps are static maps requiring reach back to the mapping
team when additional details are required.

The collapsible tree format not only provides a convenient user interface
for navigating the analysis framework, but it also demonstrates data de-
pendencies between maps. Maps that help create other maps are shown as
subnodes in the collapsible tree format, just as subfolders are collapsed in
their parent folders in a file system. For example, in Figure 9, the "Elec-
tricity Condition" map is derived from the "Electricity Generation Indica-
tor" and "Electricity Distribution Indicator" maps. Also, the "Electricity
Distribution Indicator" map is derived from the "Lighting Fuel," "Cooking
Fuel," "Has Refrigerator," and other maps. (The maps in this example
were questions chosen by the Philippine Government to best understand
their people's economic and living conditions at that time. It is unlikely
that analysts unfamiliar with Philippine society would have chosen better
questions). The collapsible tree format reduces the learning curve to un-
derstand mission-specific analysis frameworks for Soldiers and decision
makers.

Figure 9. FICUS-UI SWEAT-MSO theme hierarchy.
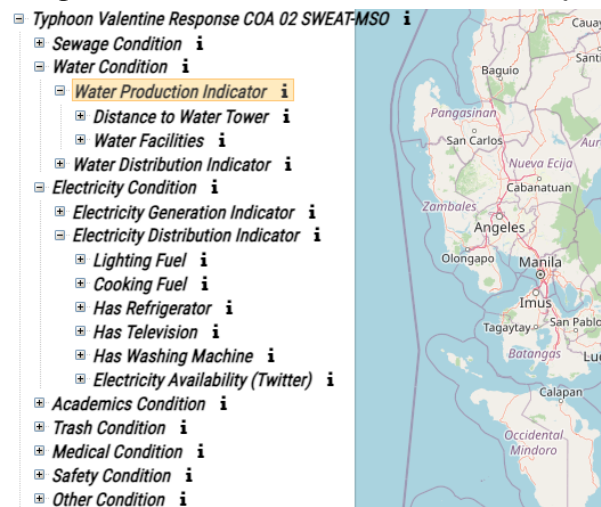
2.1.6 FICUS theme documentation

FICUS's data structures provide for geotemporal theme metadata. The US National Digital Geospatial Data Framework was established by Executive Order 12906 to provide instructions for providing metadata for all government-created geospatial maps, as well as other requirements. Metadata provides valuable information on how the data were created, how the map layer(s) are expected to be used, and (ideally) information on how to contact the map layer creators. Figure 9 illustrates how metadata are accessed from the FICUS user interface: map layer metadata information is accessed by clicking the "**i**" to the right of map name. The FICUS map server locates map data in a folder system, with each map layer having its own folder. Each map layer's metadata are given their own subfolder with a set filename for the html file providing organizing details for the metadata. Figure 10 illustrates an example metadata page. Normally, metadata should contain contact information of the map layer creators to ensure reach-back opportunities. Although not currently operational, we envision the FICUS map server to contain a simple mail server that allows end users to send an email message to the map creators.

Figure 10. Theme documentation from model outputs.

2.2   Neighborhood-scale population modeling in analytic frameworks for course-of-action analysis

The FICUS analytical framework will help to visually identify geospatial patterns and social behavior in vulnerable locations. When military combat or a natural disaster impacts an area, the population is often not prepared. Many locations, particularly urban, lack adequate architectural infrastructure and likely have less chance of recovery in light of such events. To evaluate a region with this prototype, large data sets and simulations were used. Conventional computers do not have the capacity to efficiently integrate the enormous amount of information required for the task. Therefore, the testing was done using The Center for High Performance Computing (HPC) to achieve optimal and realistic answers during the modeling process.

2.3   Neighborhood-scale population modeling

Population modeling in FICUS requires special data structures incorporating codependences necessary to accurately represent the dozens of demographic variables in the analysis framework at neighborhood scale. Typical geodemographic techniques either aggregate population variables in separate maps (traditional geographic information system maps) or use geodemographic segmentation (which clusters similar administration areas into groups using multivariate statistics). Traditional geographic information system population maps lose the codependences between population variables, making it impossible to accurately perform more complex analyses, such as those discussed later in this report. For example, geodemographic segmentation cannot account for the variability within a neighborhood and invariably ignores minority populations (Grekousis and Hatzichristos 2012). Understanding minority populations, whether they are more vulnerable in a natural disaster or potentially leveraged by enemy forces in a conflict situation, will often be critical to mission success. FICUS creates a multiverse of every person in the study area, with each person retaining the household and personal variables. The process in FICUS, named Digital Populations (DigiPops) and originally developed in the early 2000s (Ehlschlaeger 2005), has been enhanced throughout the last decade to support dynamic urban environments.

DigiPops begins by mathematically combining survey data, imagery, maps of transportation, land use, and land cover to generate possible locations

of every man, woman, and child in an area of interest. The households and people simulated are derived from a survey or census microdata, defined as a set of questions asked using proper survey design techniques. The locations of simulated households are based on household density surface, electricity power lines, census information, ground truth samples, and other infrastructure networks. The household density map indicates the probability that a household is located at each place based on environmental and infrastructural information.

DigiPops locates known survey responses to specialized information not typically available to demographic models and ensures those locations will have survey responses coming from the same exact locations. This feature creates the ability to answer questions such as "where are poor, uneducated, and unemployed men between the ages of 15 and 35?" In a disaster encompassing a defined area, how many people will flee, or show up in local refugee camps? Or where are families with children under the age of 10? Using DigiPops information, FICUS offers detailed, household-level mapping capabilities that dramatically improve the military's situational awareness in a densely populated and complex environment.

FICUS extracts detailed social information from large scale-surveys and generates visualizations of a range of possible population distributions. Using existing spatial analysis tools, techniques, and models written in various computer languages, FICUS generates maps showing the location of individuals in a manner that if the actual population was surveyed, the results would accurately reflect what is knowable about various model inputs (Ehlschlaeger et al. 2016).

The Philippines was chosen as a region of study, and the DigiPops results was part of the decision support. The corresponding realizations for each province in the Philippines were generated by running the algorithms using HPC. This resulted in better understanding the degree and the stages of vulnerability among these geographic sites. A higher percentage of the areas studied were represented by inequality and poverty whether in a remote site or an urban area surrounded with high illiteracy and lack of basic needs.

The algorithms built in DigiPops have an executable program that allows simulations to be run in any HPC architecture. The Portable Batch System (PBS) shell scripts are straight forward and not difficult to formulate when

entering parameters for the task at hand. The queue system facilitates monitoring simulations during high demand, and the only drawback using HPC and PBS is that the script needs to be readjusted during times of high traffic.

The rapid decision making achieved by using the FICUS framework will facilitate the creation of more accurate information when evaluating regions susceptible during an emergency.

2.4 PMESII/ASCOPE framework

To help provide automation support to analysts, our team implemented a proof-of-concept association of survey data variables to an Army doctrine framework. This effort aimed to evaluate the feasibility of and provide the groundwork for a tool to help analysts discover data available to apply the Army framework. This section summarizes our proof-of-concept effort to associate data variables from the Integrated Public Use Microdata Series (IPUMS) International survey with a framework known as PMESII/ASCOPE. PMESII is an acronym used to describe operational variables—political, military, economic, social, information, and infrastructure. ASCOPE is an acronym to describe the civil component of mission variables—areas, structures, capabilities, organizations, people, and events.

2.4.1 Background

The PMESII/ASCOPE framework is described in several Army and Department of Defense doctrinal publications. PMESII and ASCOPE are combined into a "crosswalk" in Army Techniques Publication (ATP) 2-01.3, *Intelligence Preparation of the Battlefield* (HQDA 2019, 4-22). Table 4-6 from ATP 2-01.3 provides examples of information relevant to the intersection of each PMESII variable with each ASCOPE variable. Figure 11 shows a portion of Table 4-6.

Army doctrine and training suggest that one method for analysts to present some information from this table is to understand and identify key information and present it in a crosswalk matrix using the PMESII/ASCOPE fields. However, doctrine also indicates that "Because of the complexity and volume of data involving civil considerations, there is no simple model for presenting civil considerations analysis. The intelligence staff maintains this information in the civil considerations data file and constructs

intelligence products comprising overlays and assessments areas overlay to assist in planning" (HQDA 2019, 4-25). Similarly, *Civil Affairs Planning*, ATP 3-57.60, Table 4-1 provides a sample matrix of civil considerations and operational variables, indicating that "a matrix that organizes data by combining ASCOPE and PMESII-PT (—physical environment time) can assist in refining and analyzing civil considerations" (HQDA 2014, 4-19). Also, *Civil Affairs Civil Information Management*, ATP 3-57.50, provides "an example of civil analysis using PMESII-PT to break down specific groupings of raw data and then categorize that data by using ASCOPE" (HQDA 2013, B-1). As the most recent doctrine and including more examples than the other ATPs, our limited proof of concept was implemented based on the example table from ATP 2-01.3.

Figure 11. PMESII/ASCOPE crosswalk for civil affairs (Reproduced from HQDA 2019, Table 4-6. Public domain).

	Areas	Structures	Capabilities	Organizations	People	Events

POLITICAL	• Enclaves
	• Municipalities
	• Provinces
	• Districts
	• Political districts
	• Voting
	• Party affiliation areas
	• Shadow government influence areas
		• Courts (court house, mobile courts)
		• Government centers
		• Provincial/District centers
		• Meeting halls
		• Polling sites
		• Police stations
		• Prisons
			• Public administration:
			  ▪ Civil authority, practices, and rights
			  ▪ Political system, stability, traditions
			  ▪ Standards and effectiveness
			• Executive and Legislative:
			  ▪ Administration
			  ▪ Policies
			  ▪ Powers
			  ▪ Organization
			• Judicial/Legal:
			  ▪ Administration
			  ▪ Capacity
			  ▪ Policies
			  ▪ Civil and criminal codes
			  ▪ Powers
			  ▪ Organization
			    ▪ Law enforcement
			• Dispute resolution, grievances
			• Local leadership
			• Degrees of legitimacy
			• Corrections
				• Banks
				• Business organizations
				• Cooperatives
				• Economic nongovernment organizations
				• Guilds
				• Labor unions
				• Major illicit industries
				• Large landholders
				• Volunteer groups
					• United Nations representatives
					• Political leaders
					• Governors
					• Councils
					• Elders
					• Community leaders
					• Paramilitary members
					• Judges
					• Prosecutors
					• Law enforcement officers
					• Corrections officers
						• Elections
						• Council meetings
						• Speeches (significant)
						• Security and military training sessions
						• Significant trials
						• Political Motivation
						• Treaties
						• Will

MILITARY	• Areas of influence • Areas of interest • Areas of operations • Safe havens or sanctuaries • Multinational/local nation bases • Historic data on operations by the opposition	• Bases • Headquarters (police) • Known leader houses/businesses	• Doctrine • Organization • Training • Materiel • Leadership • Personnel manpower • Facilities • History • Nature of civil-military relationships • Resource constraints • Local security forces • Quick-reaction forces • Insurgent strength • Enemy recruiting	• Host-nation forces present • Insurgent groups present and networks • Multinational forces present • Paramilitary organizations • Fraternal organizations • Civic organizations	• Key leaders • Multinational, insurgent, military	• Combat • Historical • Noncombat • Kinetic events • Unit reliefs • Loss of leadership
ECONOMIC	• Commercial • Fishery • Forestry • Industrial • Livestock dealers • Markets • Mining • Movement of goods/services • Smuggling routes • Trade routes • Black market areas	• Banking • Fuel: distribution, refining, source • Industrial plants • Manufacturing • Mining • Warehousing • Markets • Silos, granaries, warehouses • Farms/Ranches • Auto repair shops	• Fiscal: access to banks, currency, monetary policy • Can tolerate drought • Black market • Energy • Imports/Exports • External support/aid • Food: distributing, marketing, production, processing, rationing, security, storing, transporting • Inflation • Market prices • Raw materials • Tariffs	• Banks • Business organizations • Cooperatives • Economic nongovernment organizations • Guilds • Labor unions • Major illicit industries • Large landholders • Volunteer groups • Police departments	• Bankers • Police • Employers/Employees • Labor occupations • Consumption patterns • Unemployment rate (if exists) • Job lines • Landholders • Merchants • Money lenders • Black marketers • Gang members • Smuggling chain	• Drought, harvest, yield, domestic animals, livestock (cattle, sheep), market cycles • Labor migration events • Market days • Payday • Business openings • Loss of business

2.4.2 Design

Army analysts working with the researchers indicated that the PMESII/ASCOPE framework is often used during IPB. Time-consuming steps include collection of data, discovery and understanding relevant

data, and preparation of analytic products. Analysts may collect IPB data from diverse sources; however, IPUMS was not one of the typical sources. Analysts then use the collected data to prepare the products, such as described in doctrine—including maps, summary lists, data tables, and others, to include a matrix-like summary.

The team aimed to enable analyst use of survey data by providing a repeatable, simplified approach consistent with a framework that analysts are accustomed to using. The survey data used included information on the locations from which responses were sampled and provided rich, detailed information about respondents and their households. The HGDemo team worked to first depict the survey data in spatial representations, characterize differences over the operational environment, and finally, integrate that data with other models and simulations.

To depict the survey data with the PMESII/ASCOPE framework, the team designed an approach that included a matrix-based representation of the available data, preconfigured variables associated to each cell in the matrix, and finally, user selection of specific variables of interest. Figure 12 summarizes this design, which serves as a mock-up for potential user-interface designs:

- *Left*: Small PMESII/ASCOPE matrix with different colored cells indicating where data exists or is lacking
- *Middle*: "Political Areas" and subset of IPUMS list
- *Right*: Map with title—Political Areas—IPUMS item, colorized map.

This design will allow analysts to efficiently discover and explore the survey data as arranged according to the PMESII/ASCOPE framework and thus related directly to doctrinal examples of potentially relevant considerations. By depicting the available data in matrix form, the analyst will be cued to framework elements that may be addressed or partially addressed using the survey data.

Figure 12. Mockup of workflow and interface for PMESII/ASCOPE framework to survey data.
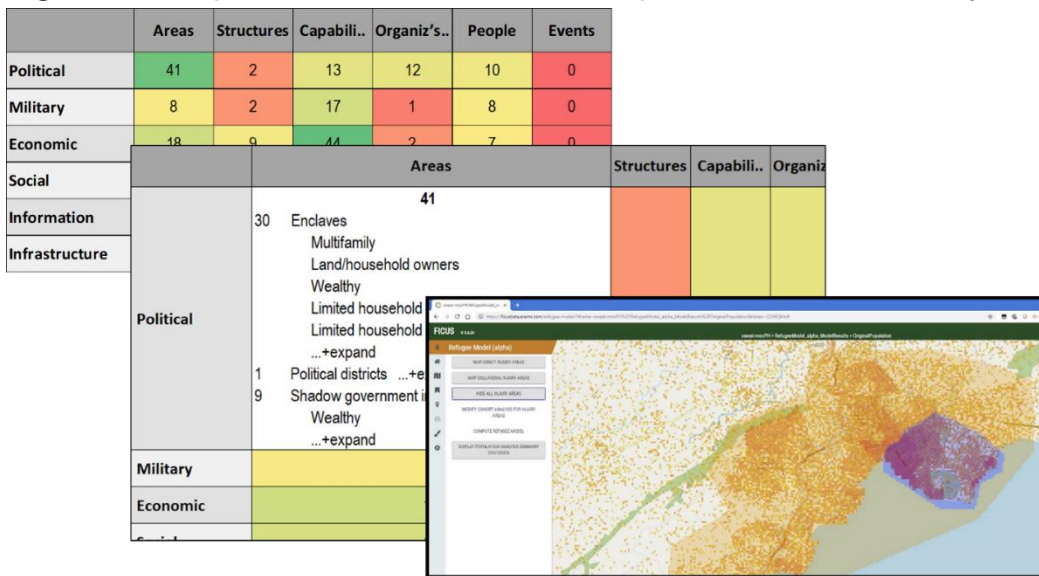
On examining the data variables that support the framework element and the examples, the analyst may personally determine whether the information available may be operationally relevant. And, on relevance determination, the analyst may examine the actual data and associated maps to determine if the maps, or a derivative item, would be a useful IPB product. For data the analyst deems relevant, they may choose to include the source map as a PMESII/ASCOPE map product and record a recommended finding in the associated cell in the matrix.

In addition to including individual maps, combining data elements using a weighting scheme will provide useful information. For example, the analyst may determine specific, important administration areas relevant for a particular mission. The analyst may also decide that rather than multiple maps to indicate key political factors, they only want an important summary map to show the conflation of multiple data layers. For example, the percentage of population that have occupations as elected officials, government workers, or military workers within an administrative area. The analyst may also elect to weight the input of the composite map such that the elected officials or military workers are given greater emphasis. Showing locations with large proportions of elected officials, government workers, or military workers may provide useful information during a civil disruption.

2.4.3 Solution

The proposed solution is designed to help analysts efficiently use and explore survey data with the PMESII/ASCOPE framework.

To complete this proof-of-concept, the team created a database to organize the survey data variables, the PMESII/ASCOPE variables, and examples. The database includes several tables and queries, with the table names and attributes in the unified modeling language database diagram (Figure 13).

Figure 13. PMESII/ASCOPE framework tables.
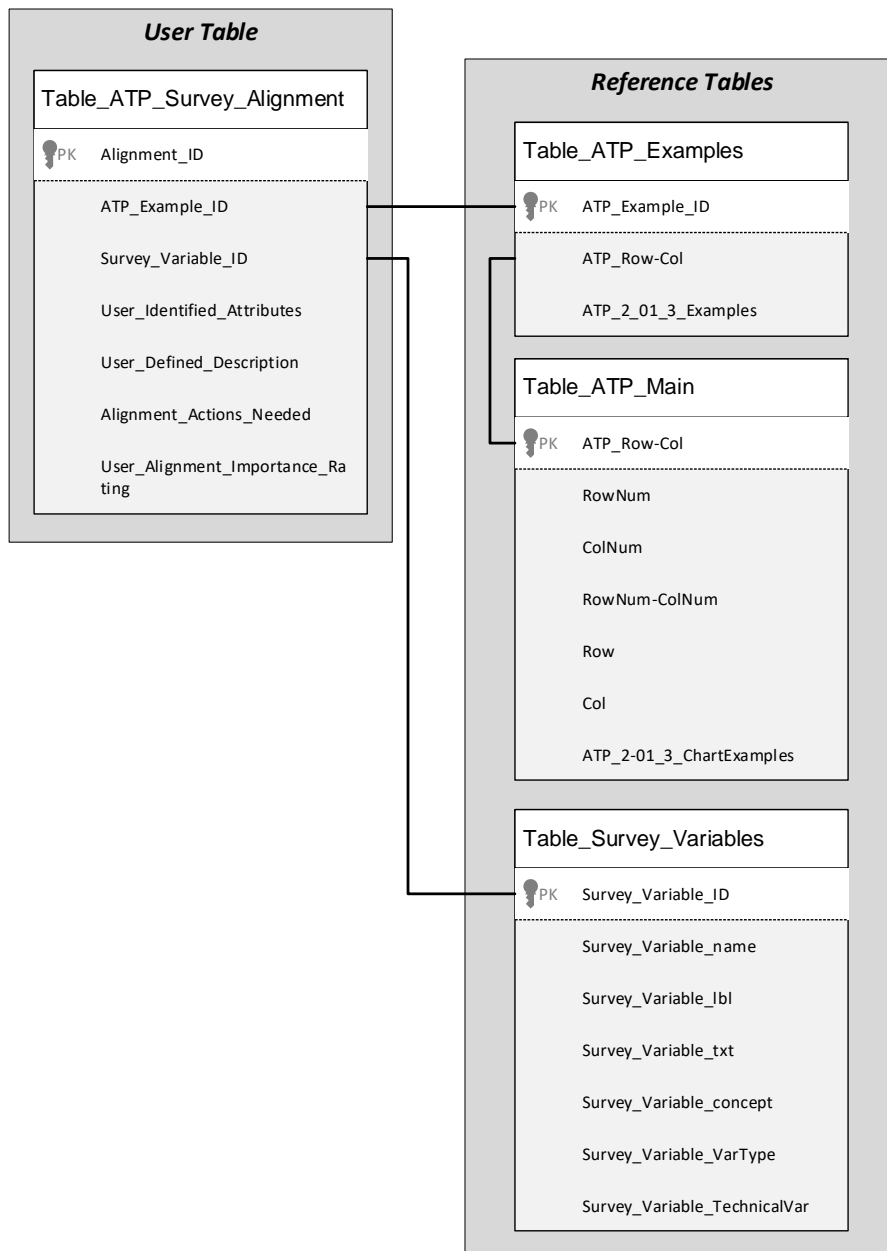
As currently implemented, the attributes of Table_ATP_Survey_Alignment include the following:

- Alignment_ID: a unique identifier for each association prepared
- User_Defined_Description: brief description of the alignment idea
  - For example, the user reviews the doctrinal examples and identifies economic areas that include "livestock dealers" in the survey information about occupation. In those occupations, the user may find attributes that include farm-affiliated or animal-affiliated occupations that they believe are closely associated. The user may then provide a description: "Livestock area based on farm occupations."
- ATP_Example_ID: association of the alignment idea to the crosswalk
  - In the example above, the user would select example ATP_Example_ID = 112, which has ATP_Row-Col = "Econ-Area" and ATP_2_01_3_Examples = "Livestock dealers."
- Survey_Variable_ID: association of the alignment idea to one or more survey variables
  - In the example above, the user would select Survey_Variable_ID = "PH2000A_0422" (which has Survey_Variable_lbl = "Occupation").
- User-Identified_Attributes: documentation for each survey variable, what attribute characteristics are needed to support the alignment idea
  - In the example above, the user would then review documentation of the survey variables and discover that "621," "622," and "629" are relevant responses, indicating a variety of farmers and animal raisers. The user may then enter "PH2000A_0422=621 OR 622 OR 629" into the field.
- Alignment_Actions_Needed: any additional work needed to complete implementing the alignment idea with the data
  - For example, if the team or individual preparing an idea determines that the attributes identified are incomplete, or a complex query must be prepared, or more research may be necessary to make an idea work, the user may capture notes about the remaining actions necessary.
- User_Alignment_Importance_Rating: qualitative assessment by the user of the degree (on a scale of 1–10) to which the alignment idea fulfills the intended purpose of the PMESII/ASCOPE example
  - In the earlier example, economic areas includes "Livestock dealers" as a doctrinal example. People that report their occupation as an

"animal raiser" are likely relevant to the doctrinal example and probably deserve a high rating.

o Political areas includes "enclaves" as an example; a high-rating may be merited if the survey data can be used to discern areas that have distinct characteristics from the surrounding areas, such as whether the population speaks the native language(s). This may be scored highly (8–10).

o However, if the data includes examples of religious population groups, a high score may be appropriate for the "Religious groups" example under "Social-Organizations." However, "Social-Events" includes 'Religious holidays," which, spatially, could be partially informed by the "Religious groups" information.

2.4.3.1 Proof of concept implementation

After implementing the database described above, the research team prepared a preliminary proof of concept, populating the database with alignment ideas. The proof of concept included over 100 straight-forward, completed ideas where the researcher scored the importance as three or higher. The research team used the PMESII/ASCOPE crosswalk with counts as shown in Figure 14 below.

Figure 14. PMESII/ASCOPE crosswalk.

	Areas	Structures	Capabilities	Organizations	People	Events
Political	9	2	9	9	4	0
Military	4	2	6	1	5	0
Economic	8	4	14	0	4	0
Social	7	1	4	0	0	0
Information	0	1	6	0	0	0
Infrastructure	3	4	2	0	0	0

As this work served as a proof of concept and has not undergone review and refinement, only a small set of examples are provided here. The outline below has multiple levels; the first level indicates the cell in the crosswalk, the second level indicates the PMESII/ASCOPE example from doctrine (contained within the cell of the crosswalk in ATP 2-01.3); the third and beyond levels indicate a concept or variable and attribute from the survey. This mimics the design idea presented earlier.

- Political Area
  o Enclaves

- * Does not speak the primary language of the country
- * Wealthy
  - ~ Owns land
  - ~ Owns other land
  - ~ Building condition is well-maintained
- * High educational attainment
- * Low educational attainment
- Political Structure
  - o Government centers
    - * Occupations
      - ~ Government workers
      - ~ Military workers
      - ~ Elected officials
- Political Capability
  - o Judicial/legal
    - * Occupations
      - ~ Legal professionals
      - ~ Law enforcement
  - o Legislative
    - * Occupations
      - ~ Legislative officials
  - o Public administration
    - * Occupations
      - ~ Federal government workers
      - ~ Regional government workers
      - ~ Local government workers
- Political Organizations
  - o Nongovernment organizations
    - * Employment sector
      - ~ Foreign government or nongovernment organizations
- Political People
  - o Judges
    - * Occupations
      - ~ Legal professionals
  - o Community leaders
    - * Occupations
      - ~ Traditional chiefs and heads of villages
      - ~ Senior officials of special-interest organizations
      - ~ Directors and chief executives of corporations
      - ~ Officers

- Military Area
  - o Area of influence
    - * Occupations
      - ~ Officers
      - ~ Enlisted personnel
    - * Housing type
      - ~ Group quarters
        - Military barracks
- Military Structure
  - o Bases
    - * Housing type
      - ~ Group quarters
        - Military barracks
- Military People
  - o Key leaders
    - * Occupations
      - ~ Officers
- Economic Area
  - o Commercial
    - * Occupations
      - ~ Proprietors
      - ~ Sales supervisors in wholesale or retail
      - ~ Cashiers, tellers, other clerks
      - ~ Salesperson
      - ~ Market stall vendor
- Economic Area
  - o Livestock dealers
    - * Occupations
      - ~ Livestock and dairy farmers
      - ~ Poultry farms
      - ~ Other animal raisers
- Economic Structure
  - o Fuel: distribution
    - * Household access
      - ~ Access to energy
      - ~ Access to lighting
- Economic Capability
  - o Fiscal—access to banks
    - * Household
      - ~ Owned, paying loan from bank

- o Food
    - * Occupations
        - ~ Agriculture—fruits, vegetables, grain
        - ~ Food manufacturing and processing
        - ~ Food distribution

2.4.3.2 Recommendations

In the near future, the research team plans to refine the database structure to better support selecting multiple variables and attributes from the survey metadata. This will allow easier composition of ideas, increased transparency to what is being selected, and support automation of transforming ideas in the database into queries used to generate maps from the survey data. The research team recommends that a qualified team proceed to populate the database with ideas and incorporate a validation or evaluation process to ensure that the ideas are reasonable. This will provide a sound basis for the next recommendation. As a related effort, the research team recommends the use of a vector-space model, or similar technique, to help automate the association of survey attributes with PMESII/ASCOPE variables and examples. Such an implementation would allow the ingest of new survey metadata and their rapid association to the categories. On such implementation, the evaluated data set can be used to assess the performance of the automated method.

2.5 Refugee and population dynamic models supporting situational awareness

According to the United Nations Refugee Agency, there are approximately 85.6 million people who were forcibly displaced from their homes (UN-HCR 2022). As of 2017, some 50 million people in cities around the world bore the brunt of the atrocities of urban warfare (ICRC 2017); this number is projected to increase. The war-ravaged cities of Aleppo, Mosul, Sana'a, Mogadishu, Gaza, Marawi, and others have witnessed the most violent conflicts of the decade. Ordinary civilians, trapped in sieges, have become the defining feature of the battlefield. "Refugees as weapons," or "weapon of mass migration" became common terms used to describe the exploitation of human mass migration—whether voluntary or forced—by state and nonstate actors to achieve political, military, economic, or propaganda objectives.

Never before has the importance of understanding and predicting refugee and population dynamics become more urgent. Developing a comprehensive and robust situational awareness of these dynamics has direct tactical and strategic implications for the US and its partners and allies. In addition to conflict, cities also suffered from recent megadisasters, such as the Haiti earthquake, Indian Ocean earthquake, Cyclone Nargis, Great Sendai Earthquake, Super Typhoon Haiyan, Indian and Pakistan heat wave, etc. Approximately three in five cities, or one-third of the world's urban population, are currently at high risk of natural disasters (UN DESA 2018).

Many studies predict that urban conflict and climate-induced catastrophic events are going to be the new normal in today's rapidly burgeoning and unplanned urbanization. By 2050, about 2.5 billion people, or roughly 68% of the world's population, would be living in urban areas. Nearly 90% of this population growth would be coming from Asia and Africa where many unstable states, vulnerable to natural hazards, remain in conflict (UN DESA 2018).

Cities make an attractive target to adversaries. Increased urban connectivity has allowed small groups of nonstate actors to shutdown entire cities at will, simply by controlling key access points. Urban warfare has also made it possible for small armed groups to wield significant political and military influence out of proportion to their size. State and nonstate actors have used the hectic flows of urban life to conceal their capabilities and actions. Extremist organizations could easily recruit the local population to instigate civilian unrest through propaganda and misinformation and hide in densely populated areas to evade arrest.

A nuanced understanding of the human system in urban warfare becomes a critical factor in mission accomplishment. Nonstate armed violence in cities tends to be protracted and pose a formidable threat to a nation's stability and security. Cities are particularly vulnerable to chemical, biological, radiological, and nuclear (CBRN) weapons, pandemics, and conventional attacks on critical infrastructure, such as subway systems and electrical infrastructure. A solid understanding of how the local population would react, where they decide to flee, and how different social groups would respond to military operations would be vital in force protection, controlling the escalation of violence, mass hysteria, and in shaping populace opinions towards military actions.

Operations must be planned and executed based on a comprehensive analysis of the city, including its human-physical touch points. Each urban operation must be examined in the context of its location. In particular, the weaponization of mass migration by both state and nonstate actors makes it more urgent for commanders to stay ahead of the curve and prepare for any civil-military interventions that could help turn the tide of war or help shape the operational environment. However, intelligence on the complexity and interconnectedness of the urban physical and human system remain inadequate. These informational gaps will inevitably drive and shape the next wave of military intelligence in both conventional and unconventional warfare.

2.5.1 Solution

Large cities with millions of people spread over hundreds of square miles cannot be circumvented. The human system becomes a critical component in military planning and operations in urban warfare. Despite increasing conflicts in urban settings, the military remains relatively inexperienced fighting in densely populated environments. It is crucial for future military operations to establish a detailed grasp of urban population characteristics, attributes, and movements to ensure mission accomplishment and prevent adverse opinions of military actions.

Currently, social data, such as income, housing, ethnicity, religion, and occupation, is traditionally only available at resolutions of 1 km or greater. Our model, FICUS, uses DigiPops (Ehlschlaeger 2005), which allows us to extract more spatially detailed information from these relatively gross spatial data. DigiPops generates multiple realizations of populations, also known as a "multiverse," distributed across a study area while accounting for the uncertainty in the source data. Because the best estimate of the location of people may be misleading, the DigiPops multiverse permits queries and analyses to be seen as a range of potential outcomes. With DigiPops in FICUS, analysis results are no longer a single estimate but a range of results representing the consequences of uncertainty in the input data and process models.

2.5.2 Applications

We chose the Philippines as our case study due to the frequent occurrence of natural disasters, terrorist threats, and its strategic location adjacent to the South China Sea. The Battle of Marawi benefited from FICUS output in

predicting how many of the local population would be killed, shelter in place, evacuate to an internally displaced persons (IDP) camp, or flee someplace other than an IDP camp Figure 15.

Figure 15. Prototype FICUS-UI running refugee model.
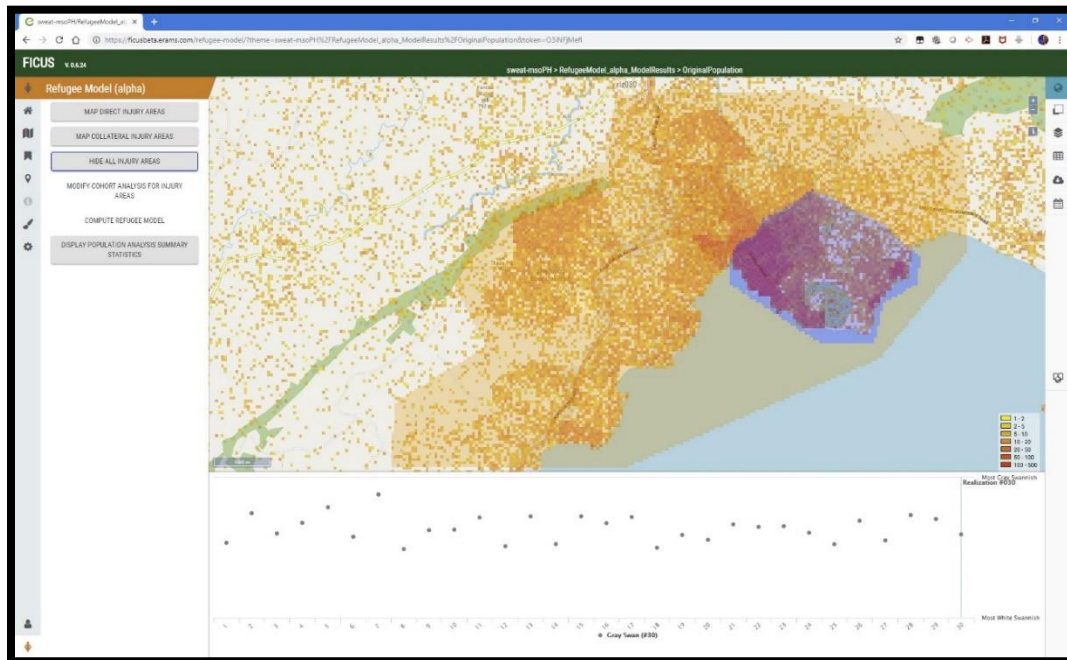
Located in Mindanao where about 6 million Muslim minorities live in the 97 million predominantly Christian country, Marawi experienced decades of peace and prosperity. While conflicts abound in the southern part of the Philippines, Marawi remained stable and nonviolent, untouched by strife since 1980 when it was legally declared as the Islamic City of Marawi with 92% of its population as Muslims. The minority Christians living in Marawi coexisted peacefully with the Muslims.

Thus, no one foresaw the fighting that broke out in May 2017 between the Armed Forces of the Philippines and the terrorist militants who declared themselves aligned with the Islamic State of Iraq and the Levant (ISIL), though the relationship remains unclear. Initially predicted to last two weeks, the ensuing five-month conflict required immediate analysis of the human system of the city.

However, since Marawi remained stable for many years, it was not in the radar of many analysts. Many civilians who decided to shelter in place also thought the conflict would end in two weeks at the most. While many violent conflicts occur in southern Philippines, active, armed confrontations

generally do not last more than a week. Thus, understanding the intricacies of Marawi's human-physical system was urgently needed, but information was not readily available.

As the fighting dragged on, the civilians trapped in the city were used as hostages by the small, armed militant groups, making it difficult for government forces to attack and neutralize the extremist group who had seized control of the city for many weeks. The weaponization of masses also occurred with the forced mass migration of the moderate Muslims out of the city. Had FICUS capabilities existed at the outset of the conflict, refugee estimates could have been computed in minutes, including the number of civilians expected to be killed, shelter in place, evacuate to an IDP camp, or flee someplace other than a refugee camp. On request, an estimate of moderate Muslims would also have been provided in a matter of minutes, allowing the Philippine government to provide civil-military interventions before the rapid deterioration of Marawi. Estimates would have included the various cohorts of people. Figure 16 shows prototype FICUS output indicating different population cohort totals becoming refugee camp residents, both short term and long term.

Figure 16. Prototype IDP model results.
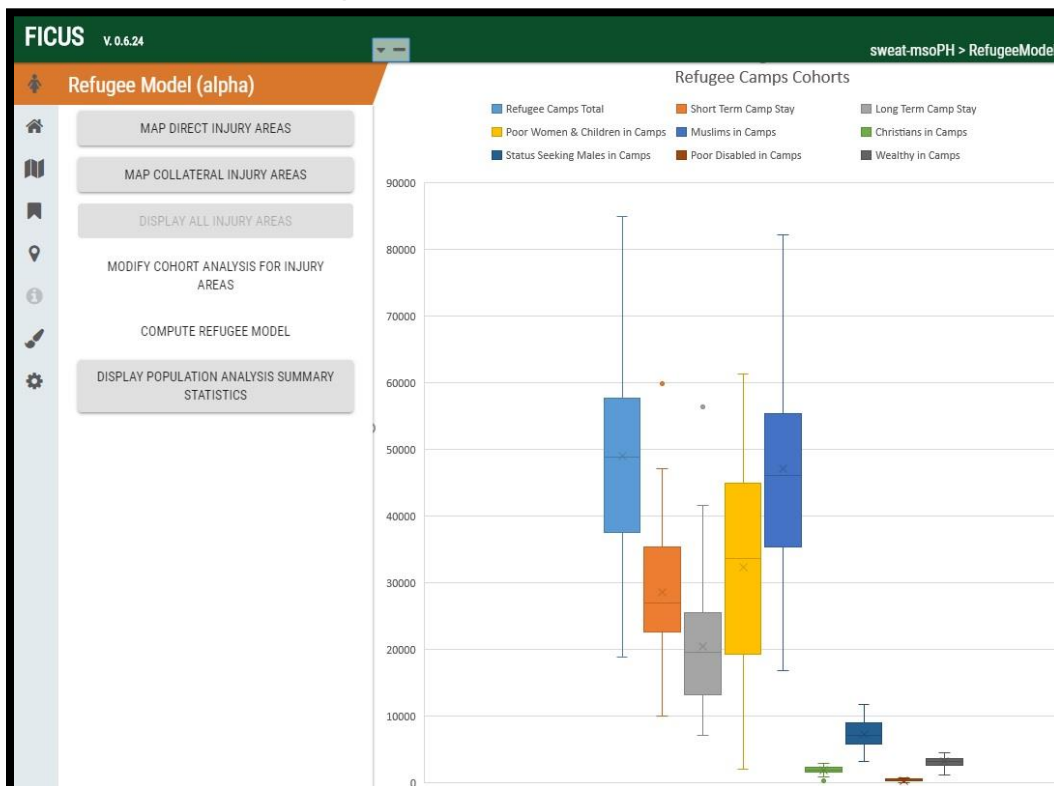
2.5.3 Modeling goals

In the use case, intelligence analysts with very little understanding and background of the Marawi area and virtually no experience using the system were asked to enter a limited set of information in FICUS. In a matter of minutes, FICUS mapped outputs of the projected impact of military operations on the local population with a particular emphasis on forced migration. Minimizing the amount of information required was one of the primary modeling goals of the FICUS research enterprise. Novice analysts were able to quickly provide products on par with seasoned analysts and subject matter experts through the use of FICUS.

Users were simply asked to identify their area of interest by drawing polygons within a map interface (see Figure 30). FICUS would then generate the population subgroups and, in this use-case example, those most likely to have sheltered in place, evacuated to an IDP camp, fled the region, or have been killed, including an associated range of probabilities in the area of interest (see Figure 17).

Figure 17. Prototype IDP model query interface.

Since the multiverse represents the locations of people household by household, these polygons could precisely locate where specific injuries would occur. For example, a typhoon may have multiple types of direct injury events: surge floods, rain and wind damage, infrastructure damage, and collateral injury locations, such as looted areas. FICUS would determine the range of potential scenarios for each type of injury event.

In addition, FICUS could also map various potential scenarios regarding the largest concentration of mass migration, whether in refugee camps, nearby towns and cities, or in conflict zones. It could also approximate where the largest casualties will occur geographically, not just because of the location of the direct impact of man-made or natural disasters, but also the likely decisions that each segment of the demographic population would likely take.

2.5.4 Modeling steps

FICUS population modeling requires data to be collected during the IPB because the population multiverse model requires significant computation time to accurately represent both the first- and second-order population relationships. Subject matter experts (SMEs) map the locations of affected civilians using available human intelligence (HUMINT), geospatial intelligence (GEOINT), and open-source intelligence (OSINT). FICUS ranks the impacts of an event from the most injurious to least injurious. SMEs will identify cohorts of the population and the range of probabilities each cohort would face for a specific injury type. These probability ranges are similar to the multiverse ranges: they go from the lowest possible value to the highest possible value.

2.5.5 User interface

First, the user zooms and pans in the region of interest and visualizes the locations of households. Second, the user traces out the anticipated affected locations, combat (or direct) areas, and collateral (or indirect) areas. Third, queries are entered that divides the population into subcategory descriptions. Figure 17 shows the interface during a sample analysis.

The *green-colored entry boxes* allow the analyst to capture queries to define each of the population cohorts. The *larger box* is a query associated with the label in the *top box*. The *six boxes associated with the labels "Indirect Zone" and "Combat Zone"* are used to define quartile ranges using

five values that set the distribution of the probabilities of individuals in the subpopulation and, in the Marawi use case, the dying, fleeing, remaining, or those ending up in IDP camps.

The *first value in each box* is the lowest conceivable probability that the cohort person or household would become that result, assuming they had not been placed in an earlier query. The *last value in each box* is the highest conceivable probability, with the *middle values* indicating the boundaries of the quartiles. Quartiles provide elegant tests when calibrating and validating the model. The various *lavender buttons* allow the analyst to select a query to edit, run a test on the queries, and view test results. The *yellowish boxes* show results of test analyses.

This interface works on an office computer on a small sample of one population realization. When the analysts are satisfied that the defined analysis correctly captures their understanding, it is time to unleash the analysis on the full set of population realizations. At this time, the analyst requests that an analysis script be generated that runs the defined analysis on the entire multiverse, which typically runs on a high-performance computer. Through the user interface, an analyst is able to run a quick analysis using the queries to check that the anticipated result estimates are reasonable.

Once the result estimates are deemed reasonable, the full set of population realizations run through FICUS, and the results will deliver detailed predictive outcomes of the various courses of actions a commander may take and their impact on the local population, including estimates on the total number of casualties and population displacement. These estimates are also tied to specific geographic locations, which informs critical plans in high-pressure, high-cost, and time-sensitive military operations. Currently, there is no equivalent capability in both public and private sector for these types of calculations and estimates.

2.6 Disease risk and vulnerability

This section describes a disease risk model implemented in FICUS using the demographic tools described in Section 2.3. The model provides a regional risk of mosquito-driven outbreaks and was accomplished via a full stochastic simulation. A robust mathematical model combining human biology with the mosquito life cycle and interactions was developed, incorporating remotely sensed information about climate (temperature,

precipitation, wind, etc.) and land cover usage. Further, this model includes recent advances in disease modeling to incorporate factors of effective population screening and heterogeneous interaction between the mosquito and human populations. The risk maps were then generated via 10-year simulations, tracking the maximum infected proportion of the mosquito and human populations.

This process, however, can become iterative. In the context of the Battle of Mawari, decision makers are presented with an understanding of what portions of the population will need to be temporarily rehomed into refugee camps. These camps are resource intensive; thus, site selection for them should be done with full situational awareness. Further, vector mobility in and out of camp areas can result in disease transfer between refugee and nonrefugee populations. With the developed framework, synthetic training tools can be implemented to allow decision makers to explore the health outcomes resulting from relocating the refugees to different areas. In the case where site selection is prescribed, our framework could be used to understand what land cover features of selected sites can be modified: where vector habitats need to be cleared or whether to implement chemical spraying for vector control. This reduction in disease spread can ameliorate a CMOs' potential to encourage a local disease outbreak.

2.7 Infrastructure interdependency and dynamic trafficability

Nowadays, with exacerbating environmental conditions and wide-spread terrorism activities, many urban areas are facing greater risks of disruptions. As the basis of the prosperity of modern cities, urban infrastructure systems are comprised of a series of highly interdependent components, such as the power grid, water network, fuel supply, and transportation network. Thus, local failure in an urban area could propagate easily through direct, physical connections within the infrastructure systems to cause cascading failures. In addition, the reactions of communities to the drastic changes of surrounding infrastructure conditions will be reshaped, like increasing resource foraging activities. These actions may further cause secondary damage to the urban infrastructure systems, for example, by transferring the service burden to surviving infrastructures and aggravating traffic congestion on the roads.

Many studies have attempted to predict the occurrence of natural disasters or to prevent initial terrorist attacks to control the impacts of disruptions.

However, another question that has attracted significant attention is how to take appropriate actions to alleviate the damages and help the urban area recover from disruptions as quickly as possible. Here, the latter question is the major focus in this chapter. In addition, since the conditions of urban systems keep evolving over time, it is important to study how the urban systems react to the disruptions dynamically so that decisions can be updated based on the situation at that time point and the prediction of the future. From this point of view, this study focuses on simulating the urban dynamics under disruptions.

2.7.1 Introduction to HISA-TRANSIMS simulation framework

The simulation model proposed in this study includes two main parts. The first module, HISA, is used to simulate urban infrastructure systems, including infrastructure interconnections and human resource foraging activities. The second module deploys the Transportation Analysis and Simulation (TRANSIMS) model to simulate the real-time roadway traffic conditions. The HISA simulation dynamic model is based on the urban system equilibrium model from Lu et al. 2018.

Figure 18 is an illustration of the simulation framework. The Object Modelling System (OMS) is a framework developed at Colorado State University to provide an interoperable environment for component-based models. Here, OMS provides a platform to facilitate the interaction between HISA and TRANSIMS so that these two modules can exchange information efficiently and achieve the goal of simulating urban dynamics comprehensively. In addition, this study uses multiple databases, which will be covered in detail in the following sections.

Figure 18. HISA-TRANSIMS simulation model framework.
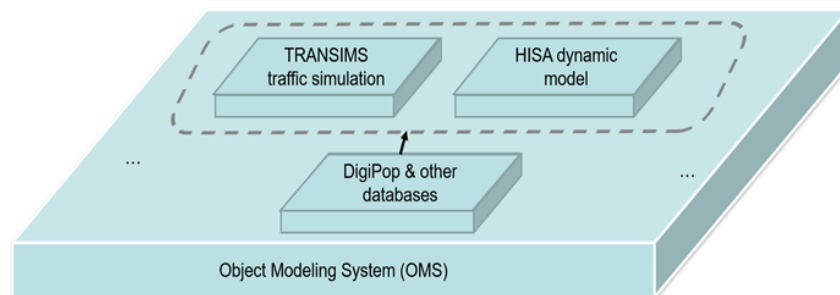
2.7.2 Urban systems characteristics analysis

The HISA model is developed to capture the urban system characteristics. In this model, the components of the urban system have been modeled into five layers, four of which are related to infrastructure systems, including the power grid network, water supply network, fuel supply system, and transportation network. They are correlated and jointly functioning to support the urban population, which is the fifth model layer in this study. The following are the details of each layer and the interconnection between them.

2.7.2.1 Power grid network

In urban areas, the power grid network typically is composed of power transmission pylons, power substations, power proxy transformers, etc. With the electricity generated from power plants, the transmission pylons are used to transmit them to the power substations, in which the high voltage current is transformed into low voltage current. Then, electricity is distributed to each transformer and serves the communities. As described above, the power grids can be modeled as a directional network with a tree structure, that is, a power transmission pylon (root) supports the substations (branches) and then provides electricity to the local transformers (branches).

These direct, physical connections within this system are very vulnerable to disruptions since failure of upstream infrastructures will likely cause a lack of power support at the downstream transformers. Moreover, the tree-like structure in this system will magnify the local disruptions and further induce cascading failures.

However, there are other methods to obtain electricity without power networks. A very common option, especially in some developing countries, is the use of diesel generators. This approach is often applied by certain infrastructures, such as hospital and water infrastructures, to maintain functionality even under emergency. In this case, it is necessary to obtain fuel to support the diesel generators via the road network.

2.7.2.2 Water supply network

The water infrastructure systems in an urban area typically include water treatment plants that purify the collected raw water, water pipelines that

transport water, and water towers and water tanks that store water. Then, water will be distributed to the population and other customers with the help of accompanying infrastructures, such as pressurizing facilities. Normal operations of water infrastructures require electricity, besides the necessary water sources, as essential input resources. Such electricity could be obtained from power grids or diesel generators.

For countries with less developed water-supply networks, many of the population may not have access to water via pipelines or water faucets. Instead, they can obtain water from vendor trucks or local water pumps.

2.7.2.3 Fuel supply system

In urban fuel supply systems, fuel depots or terminals are usually used to store refined fuel from outside urban areas before it is transported to gas stations via fuel tank trucks or pipelines. The population or infrastructures can also get access to the gas station and obtain fuel resources by traveling across the transportation network.

The fuel is also another essential type of resource, especially under the influence of disruptions. When there is a lack of electricity, fuel will serve as an important substitute resource for many facilities and communities.

2.7.2.4 Transportation network

The transportation network serves an important role as the backbone of the urban system: providing the ability for people to commute, conduct socioeconomic activities, obtain necessities, etc. The transportation network can be modeled by nodes and links, which respectively represent the intersections and road segments.

When a natural disaster or an intentional attack happens, the importance of the transportation network will be further stressed. With the loss of necessary resources, such as water and electricity, many households will be forced to access alternative infrastructures to obtain life-supporting resources. Also, infrastructures may themselves lose reliable supply of essential resources. Thus, a household's agent will drive (if that household has a vehicle) to procure substitute resources so as to meet the increasing demand from stressed households; for example, a water pump may need to access alternative fuel tanks after experiencing power grid failures. Because of the excessive travel demand under emergency conditions, severe

traffic congestion will form and further reduce the accessibility and increase costs to households.

2.7.2.5 Community

The complex activities of the population form an important feature of the urban system and support its proper daily operation.

When disruptions happen, some infrastructures will be compromised and fail to provide resources (e.g., power outage), which further transfers disruption impacts to other infrastructures (e.g., water outage) and communities. As a result, the disrupted population will travel through the transportation network to access necessary resources, resulting in excessive demand on the surviving infrastructure. Further, these resource-seeking trips will aggravate traffic congestion. The queue formation at the infrastructures further decreases the accessibility of the population to the life-supporting resources.

Figure 19 shows a conceptual illustration of how local population assess a water outage and its impact. When all water infrastructures in an urban area function well (represented by the *blue line* in the graph), the communities have stable water supply and can procure resources with a relatively low travel cost, as shown in part (*a*). When disruptions happened to water infrastructure, the section of *blue link* broken in part (*b*), a proportion of the population may lose water supply. Thus, they will approach another available water infrastructure to obtain water but at the expense of a longer travel distance, as shown in (*c*). Besides, due to queues formed at these infrastructures and the severe congestion, people may no longer have accessibility to the water resources, as illustrated in (*d*). Therefore, the community is compromised due to the lack of life-supporting resources.

Figure 19. Population access to water infrastructures under disruptions.
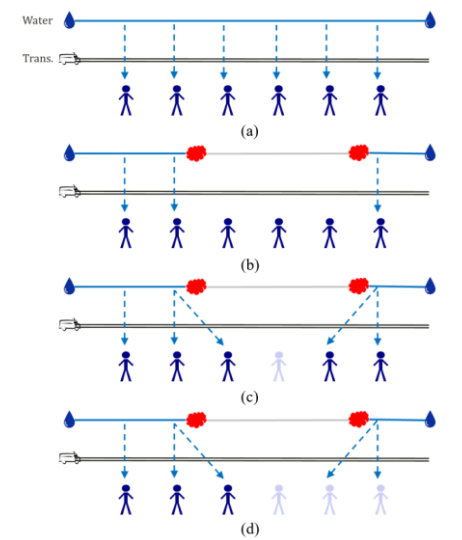
2.7.3 HISA model of urban system

2.7.3.1 Category of resource supply method

As mentioned above, the interactions between infrastructure systems are very complex. When modeling the urban infrastructure systems, two main types of resource supply methods are used.

One type is achieved by direct physical links, like power cables and water pipelines, which is noted as the "functional support" in this study. Another type of resource supply is realized by urban commodity flow carried by the transportation system (such as fuel tank trucks and water vendors). It is noted as "resource support."

These two support types exist across different urban system layers. This increases the interdependency among multiple components of the urban system. One example is illustrated in Figure 20.

Figure 20. Example of infrastructure system interconnections.
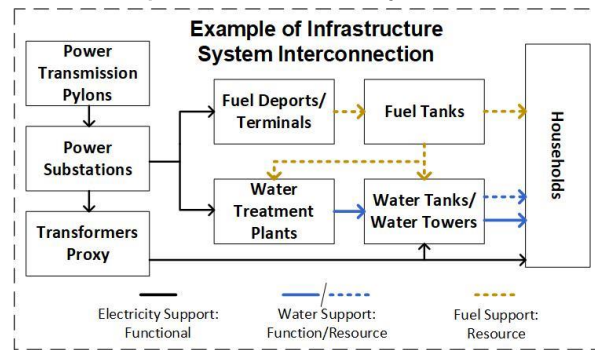
The power infrastructures, including power transmission pylons, power substations, and transformers, are connected via power cables. They further transmit electricity to support local neighborhoods and other infrastructures (such as fuel depots, water treatment plants, and water tanks). The transmission of electricity across system components is realized by functional support.

The fuel infrastructures include fuel depots and terminals and fuel tanks. By focusing on the urban area, these fuel infrastructures provide fuel resources mainly by dispatching fuel tank trucks, that is, via resource support.

Normally, the water is transported through the water pipelines between water treatment plants and water tanks, which is categorized as functional support. In addition, the water infrastructures obtain electricity from the power grids (functional support) and procure fuel by dispatching vehicles (resource support).

Through both functional and resource supports, infrastructure components in the urban system jointly work to support the community.

2.7.3.2 Disruption propagation mechanism

To capture the urban system dynamics, this study pays attention to analyzing the impacts of disruptions and capture their characteristics. When an initial disruption damages certain infrastructures, they will be compromised, and their failures will continue to propagate through system interconnections and influence other infrastructures. There are two propagation phenomena induced by two different resource support types.

For an infrastructure that receives resources via functional support, it will experience "support failure" if its upstream supporting infrastructures have failed and it does not have any substitute resources. Further, its failure will continue propagating to infrastructures that are functionally supported by it. Once an infrastructure suffers from support failure, it will remain in a malfunctioning state until its upstream supporting infrastructures are repaired.

Figure 21 through Figure 24 illustrate the process of failure propagation and recovery propagation. When extreme weather conditions strike the *power transmission pylon A* as shown in Figure 21, the substation supported by this pylon will go down (Figure 22). And the disruption will further affect the functionality of the related power transformers, causing the cascading failures (Figure 23). When *pylon A* is fixed, the recovery will also propagate and restore the functionality of downstream substations and transformers (Figure 24).

Figure 21. Support failure to recovery: initial disruptions.
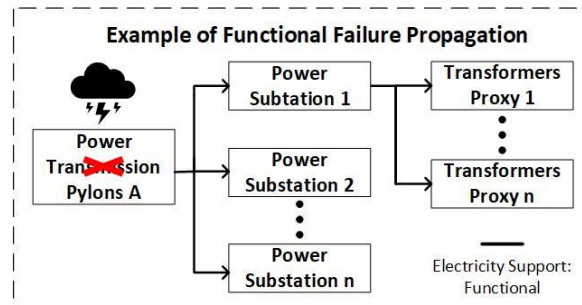
Figure 22. Support failure to recovery: support failure.
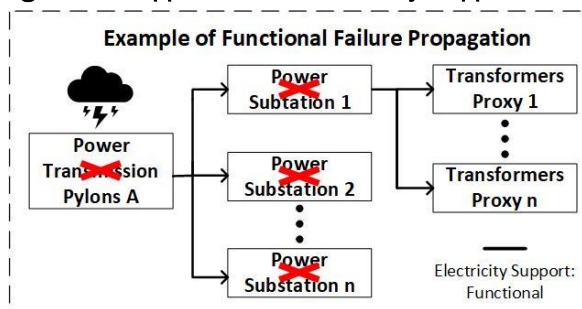
Figure 23. Support failure to recovery: support failure propagation.
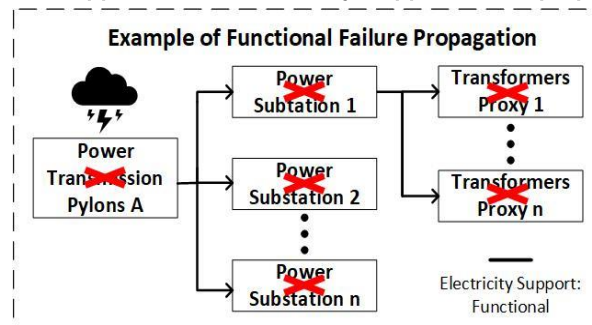
Figure 24. Support failure to recovery: recovery.
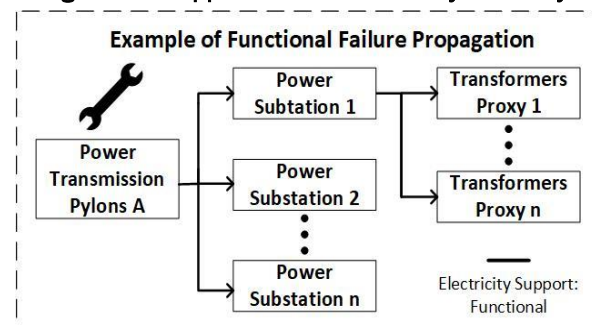
For an infrastructure that receives resources via resource support, it will face "resource failure," meaning that the resource replenishment process has been delayed. For example, a local fuel tank runs out of fuel before a replenishing tank truck arrives. This infrastructure will experience a temporary outage, and its state can be restored once the resource is refilled. The resource failure of a facility will pose an adverse impact on the society, such as forcing its customers to access resources by rerouting to remote locations. As a result, it will decrease the populations' accessibility to resources.

Some infrastructures may have multiple accesses to a certain type of resource. Take the water tank in Figure 25 as an example. It requires two essential types of resources: water and electricity (*a*). When the upstream water treatment plant fails, the water tank will experience support failure since its only access to water no longer exists (*b*). However, if its upstream power substation is disrupted, the water tank will not be compromised since it can get electricity by obtaining fuel and using a diesel generator to generate electricity (*c*). However, the water tank may face fuel resource failure after the power substation goes down.

Figure 25. Failure propagation mechanism when substitute resources available.
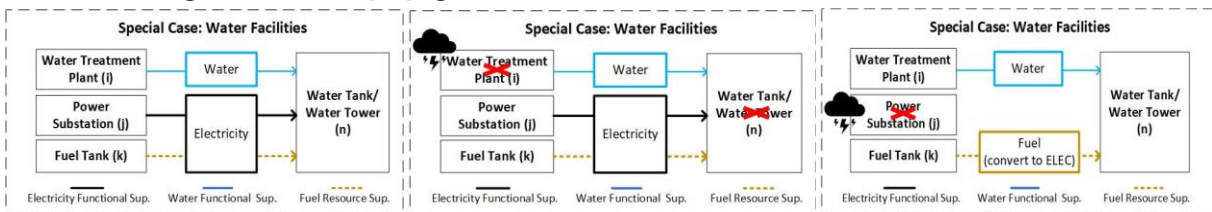
Accordingly, when modeling failure propagation, the proposed model will first determine whether each infrastructure has multiple resource access, and then propagate the effect of initial disruption accordingly.

2.7.3.3 Control policy

After determining the status of each facility based on the disruption propagation mechanism, the next important topic in this study is the interaction between population and infrastructure systems. When disruptions happen due to the drastic reduction of well-functioning infrastructures households may lose an original, stable resource supply. They will approach other available infrastructures to obtain needed resources. As a result, the remaining infrastructures could be overwhelmed and fail to satisfy all the customers' demands. To capture this phenomenon, it is necessary to figure out several problems, including how people will gather at each infrastructure spatially and temporally, how much resources will each infrastructure be able to provide, and what is the demand of each household. Thus, the model proposed in this study has been designed to keep track of the agents' resource inventory level and their trip plans. "Agent" stands for both infrastructures and households.

To address the complex activities within the urban system, control policies have been designed to study the community behaviors and keep track of the evolution of urban conditions. Here, we assume all agents in the urban system are "rational humans," meaning that they are greedy, well informed, and analytic.

Based on this assumption, the inventory control policy and the trip control policy are applied, where inventory represents the agent resource storage level.

2.7.3.4 Inventory control policy

This study deployed the "s-S" inventory control policy for each agent to determine when to obtain resources and how much resources to procure.

Figure 26 illustrates the "s-S" inventory control policy. It is based on the periodical review of the inventory level. At the beginning of each period, the agent checks the actual inventory level. If current inventory exceeds the predetermined "s" value, the agent should procure an "s-S" amount of resources. Otherwise, the agent should not dispatch a vehicle to obtain resources. The same procedure will happen in every period.

Figure 26. "s-S" inventory control policy.
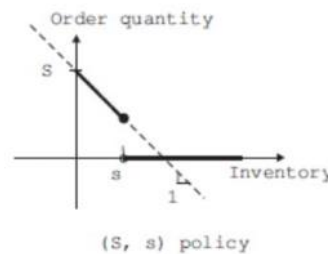
2.7.3.5 Trip control policy

Based on the dispatch time and demand determined by the inventory control policy, one blank information to be filled in is the destination of each agent's resource procurement trip. For each resource procurement trip, the proposed simulation model first examines the nearest available infrastructure that provides the corresponding resource. All information, including the origin, destination, demand, and dispatch time, serves as a plan for each agent trip, which is recorded in a file that will be used to simulate traffic.

2.7.4 TRANSIMS software for traffic simulation

The second main module in this model is the TRANSIMS simulation software, which is a regional traffic microsimulator developed under the support of the United States Department of Transportation (US DOT).

With all the trips generated from the HISA model, TRANSIMS could conduct second-by-second traffic simulation. It provides macroscopic results, such as the average congestion and average travel speed on each link, to illustrate the transportation network performance when disruption

happens. In addition, TRANSIMS also includes microscopic information in the results, such as the actual travel time of each trip, which helps to determine the time for each trip to be finished, that is, the resource replenishment of each agent. Thus, the HISA model can further update the agent inventory level based on the results from TRANSIMS.

In this section, detailed information of the TRANSIMS model is introduced. Figure 27 shows the standard workflow of TRANSIMS software. The input data of TRANSIMS include road network topology data and spatiotemporal trip demand data, which are converted within TRANSIMS and used to plan the route of each trip. The routes specify how each trip will travel across the transportation network from its origin to the destination. Based on the created routes, the microsimulator conducts traffic simulation. Then, the microsimulator provides feedback to the route planning module to modify planned routes, and this feedback loop will be executed a few times to improve the simulation results.

Figure 27. TRANSIMS standard workflow.
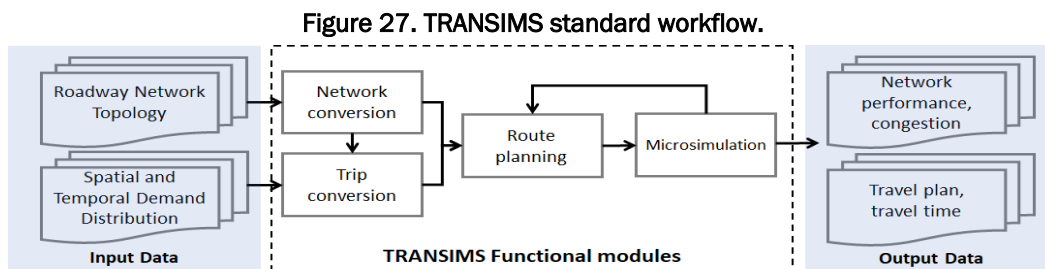
The functional module and intermediate files generated in the TRANSIMS are illustrated in Figure 28.

Figure 28. TRANSIMS functional modules and generated files.
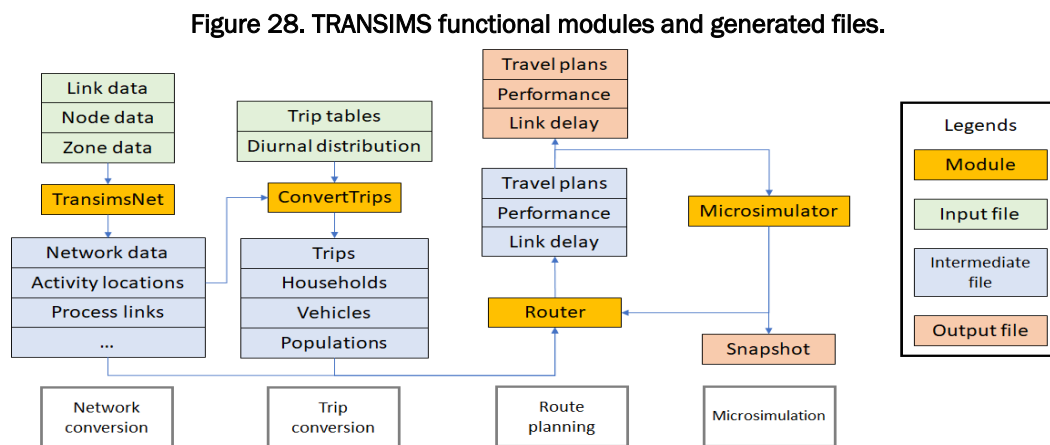
2.7.5 HISA-TRANSIMS simulation workflow

Figure 29 illustrates how these two modules interact with each other under the simulation framework.

Figure 29. HISA-TRANSIMS simulation workflow.
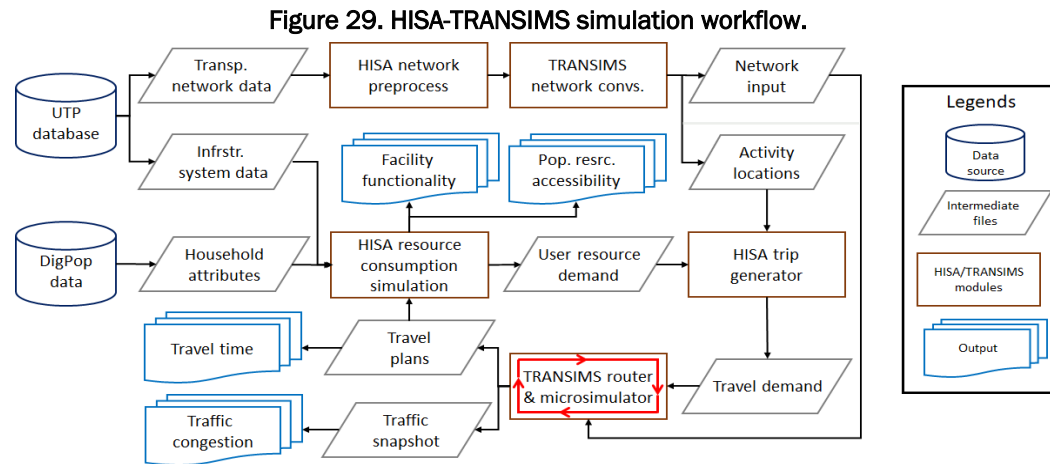
2.7.5.1 HISA-TRANSIMS input data

The databases used in this project include the Urban Tactic Planner (UTP) database and the DigiPops database. The data from the UTP database was deployed to model the transportation network and get insights into the infrastructure systems.

For the community layer, the scarcity of the high-resolution population data made it very difficult to model and predict individual behavior under the disruption scenario. Here, the DigiPops toolkit was applied to infer the information of each household based on the statistical census data through a series of random realizations. Ultimately, the neighborhood-level data were derived to provide detailed information as well as maintain the overall census characteristics of the summary statistics of the commonly used census maps. The detailed DigiPops includes household members, vehicle ownership, appliance usage, and other microdata variables not available in common datasets.

2.7.5.2 HISA initialization

The transportation network data and the infrastructure system data from the UTP database were used to initialize the infrastructure systems and the transportation network in HISA, while the household attributes from the DigiPops helped to set up the urban population in HISA.

2.7.5.3 TRANSIMS initialization

The initialization of the transportation network in HISA also transfers the data into an appropriate format so that the TRANSIMS network conversion module can read and generate network input and activity locations, which will be used in future simulations.

2.7.5.4 Simulation main body

Based on the infrastructure systems and households built from data, the HISA resource consumption simulation conducts the "inventory control policy" mentioned above to keep track of the agent inventory level and further determine the resource demand. Then, the HISA trip generator determines the details of each trip based on the "trip control policy." In addition, it will also aggregate the trip origin and destination to the nearest activity location so that the TRANSIMS router and microsimulator can recognize and execute traffic simulation. The simulation main body will loop several times so as to improve traffic simulation results. In this study, we set the number of loops to be five so as to achieve the balance between simulation performance and the time expense.

2.7.5.5 Simulation results

When the simulation loops have been finished, various results are available to view, including the travel time of each trip and traffic congestion level from the TRANSIMS, and the facility functionality and population resource accessibility.

2.7.6 User interface

2.7.6.1 User specified input

To make the simulation model compatible with different disruption scenarios, the user interface is designed as shown in Figure 30. The *left part* allows users to determine the types of infrastructures affected by the initial disruption. With the map-based interface on the *right*, users can circle out the spatial range of the initial disruptions, which is represented by the *grey polygon* on the map. Also, when drawing on the map, users have different choices of drawing methods, such as polygon and air brush. This enriches the input flexibility.

Figure 30. Input of HISA-TRANSIMS simulation model in FICUS user interface.
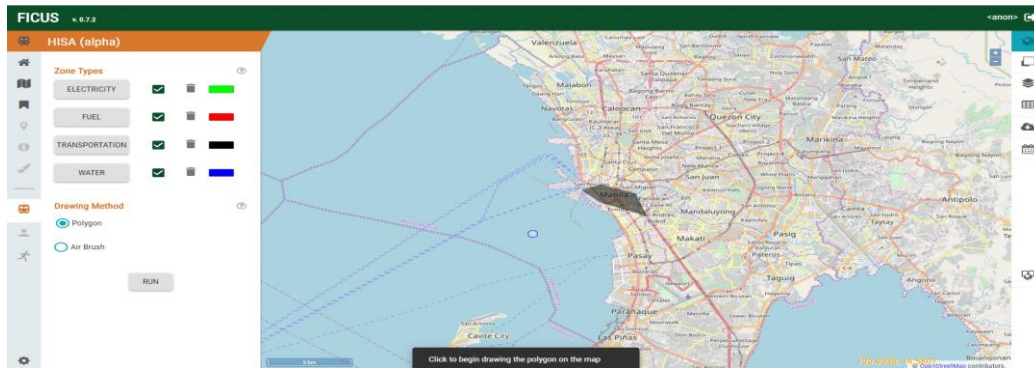
Moreover, this model also considers that multiple disruptions may strike the urban area consecutively, like an earthquake followed by a tsunami, or a series of terrorist attacks. Thus, this study is currently working on achieving the function of user-specified occurrence times of consecutive disruptions.

2.7.6.2 Output visualization

The simulation workflow generates both traffic descriptions and agent resource information. In this study, all these outputs are visualized to facilitate interpretation and decision-making. As shown in Figure 26, there are five types of results that users can choose to view. When specified, the output type will be exhibited on the map. Figure 31 shows an example of essential service impacts caused by the traffic disruptions outlined by the *polygon* in Figure 30. *Red* neighborhoods show where the most impact to water access was, and *blue* show where there was little to no impact.

Figure 31. Output of HISA-TRANSIMS simulation model in FICUS user interface.
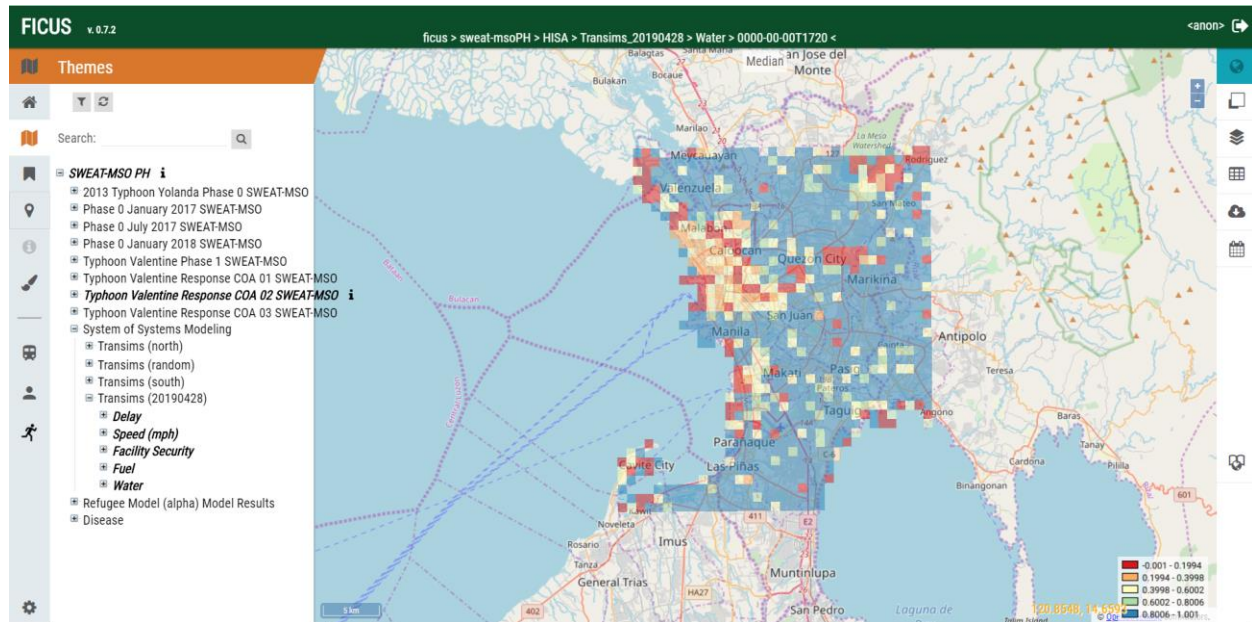
2.7.7 Case study

To demonstrate FICUS techniques, a case study was conducted for Manila, Philippines.

2.7.7.1 Background information

Manila is the capital of the Philippines, a megacity with a 24 million population, which makes it the third most populous urban area in the world. Further, this city plays an extremely important role in the economic development of the Philippines, with $141 billion GDP accounting for 47% of the national total.

However, this city also suffers from many challenges. Because of its adjacency to the "Pacific Ring of Fire," it faces many devastating disasters, such as earthquakes and typhoons. Also, the poverty rate and the spread of drugs stimulate severe social issues. Unfortunately, this city also suffers from terrorist threats, like the Resorts World Manila attack in 2017.

Thus, the proposed simulation model could help to alleviate disruption damages and quickly restore normal operations for this urban area.

2.7.7.2 Results analysis

The initial disruption was assumed to happen in the north part of Manila, at 6 a.m. on a workday. The simulation period was set to be 12 hours. The initial disruption affected four layers of infrastructures simultaneously.

After the simulation run, the facility security output represented the range of facilities affected due to initial disruption and cascading failures, as shown in Figure 32. *Red areas* in Figure 32 indicate the largest fuel disruptions with increased fuel availability ramping from *yellow*, to *green*, to *blue*, which indicates minimal or no fuel disruptions.

Figure 32. Manila case study fuel security output.
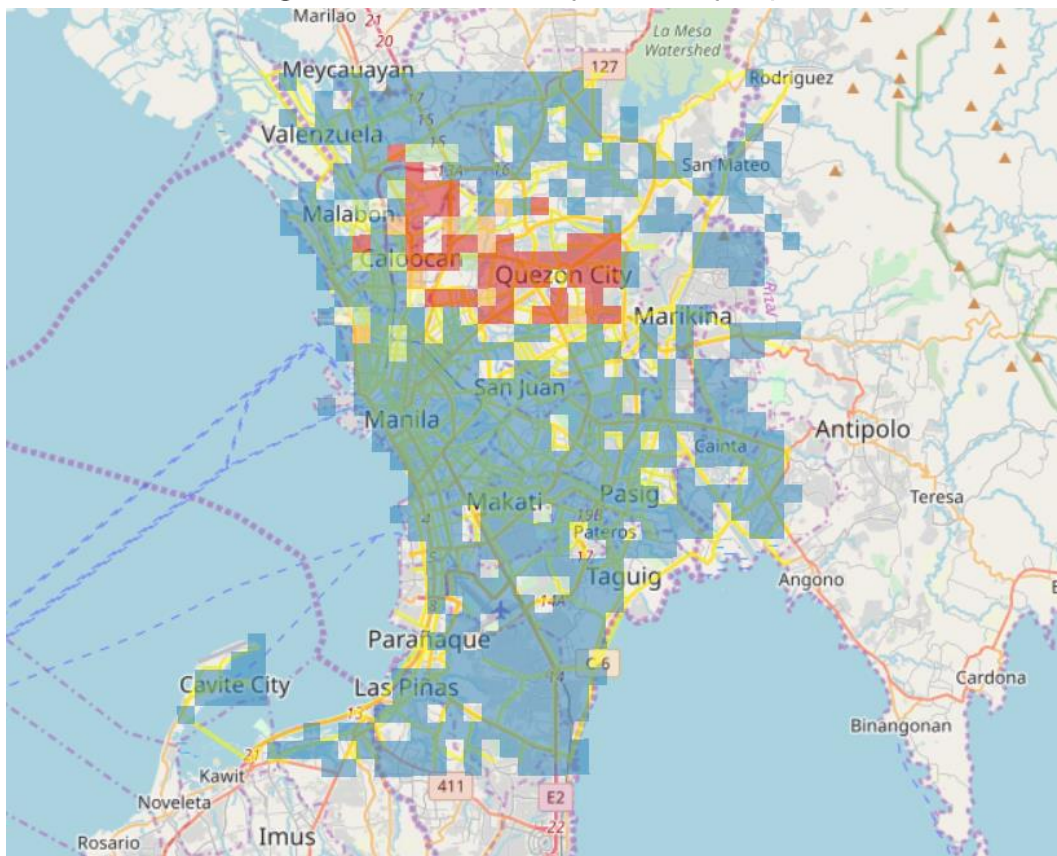
The fuel and water security outputs exhibit how the disruptions impact households dynamically while the color stands for the average household resource shortage in the grid cell.

Figure 33 shows how the cascading failures impact the household fuel inventory every two hours. Based on fuel resource evolvement, more and more households get involved because of the cascading failures. The

propagation reveals a certain pattern that the fuel shortage starts from the initial disruption area and gradually extends toward the north and east areas. In the meantime, households in other parts of the urban area are affected less. *Red* indicates maximum disruptions, while *blue* indicates minimal fuel disruption.

Figure 33. Manila case study community fuel resource security output.

| 8.00 a.m. | 10.00 a.m. | 12.00 p.m. |
| 2.00 p.m. | 4.00 p.m. | 6.00 p.m. |

The following figures show the dynamic change of the household water inventory level during the study period. Similar to the fuel, the impact of disruptions on household water inventory gradually appears and becomes drastic as time evolves. In addition, the households on the west coast are affected more significantly than those in other areas. By comparing the disruption propagation pattern from fuel security output with that from

the water security output, the water resource shortage is not as severe as the fuel shortage according to the color in affected areas, but the water shortage spreads to a larger spatial range. The comparison of two types of resource security outputs can be explained and also provides meaningful insights.

Because of the limited number of fuel stations in Manila, people relying on the fuel to obtain electricity will be drastically influenced if nearby fuel stations are compromised. However, since the majority of the population receives electricity through power grids under normal operation, they usually do not have a diesel generator. When power grids are disrupted, they still do not need to procure fuel. Thus, the failure of local fuel stations may not generate a great impact citywide. As a result, fuel security output turns out to be a great impact within concentrated areas.

On the contrary, water is an essential, life-supporting resource for the population, which can be obtained from both functional support and resource support. When disruptions strike water facilities, many households' demand will be compromised, and they will try to access water from other available infrastructures. As a result, there are excessive demands on surviving infrastructures that further reduce their capability to provide stable resource supply, which causes large-scale impacts in the urban area. However, due to many water infrastructures, households may have more available infrastructures within the reachable range. Thus, the failure of water infrastructures will cause large-scale but moderate impacts compared with fuel security output. Figure 34 shows FICUS demonstrating increasing water scarcity over time as a portion of Manila loses its water infrastructure. Water scarcity is effected in three ways: first, when infrastructure that was used for water access is damaged; second, when cascading failures affect a water source; third, when working water supplies are overwhelmed by additional people traveling to the sources from water-denied areas. *Red areas* contain the highest proportions of households with water scarcity, while *blue areas* have the highest proportion of households with enough water.

Figure 34. Manila case study community water resource security output.

| 8:00 a.m. | 10:00 a.m. | 12:00 p.m. |
| 2:00 p.m. | 4:00 p.m. | 6:00 p.m. |
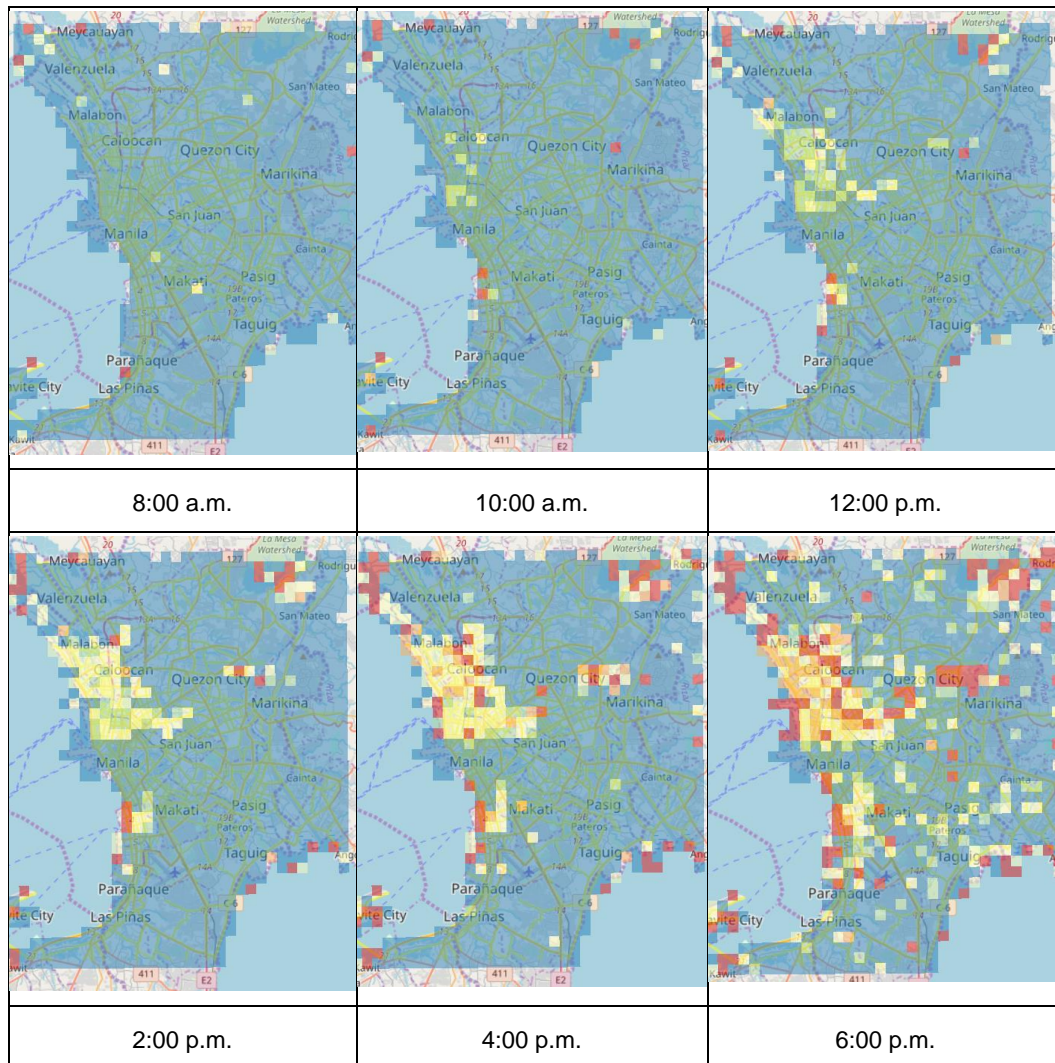
Figure 35 demonstrates a FICUS course-of-action analysis when choosing between repairing water networks for different areas in Manila. In all *three rows*, the columns of maps estimate water shortages by household in three-hour intervals after the damaging event. The redder the area the more severe the water impacts. The *top row* of maps indicates the severity of water shortages over time should no repairs happen. The *middle row* of maps demonstrates the events if the northern half of the damaged infrastructure is repaired 12 hours after the damaging event. The *bottom row* maps show similar events except for the southern half. The FICUS model accounts for the second-order effects 18−24 hours after the damaging event when people from the water scarce regions of Manila begin using the repaired infrastructure.

Figure 35. HISA output in time series.
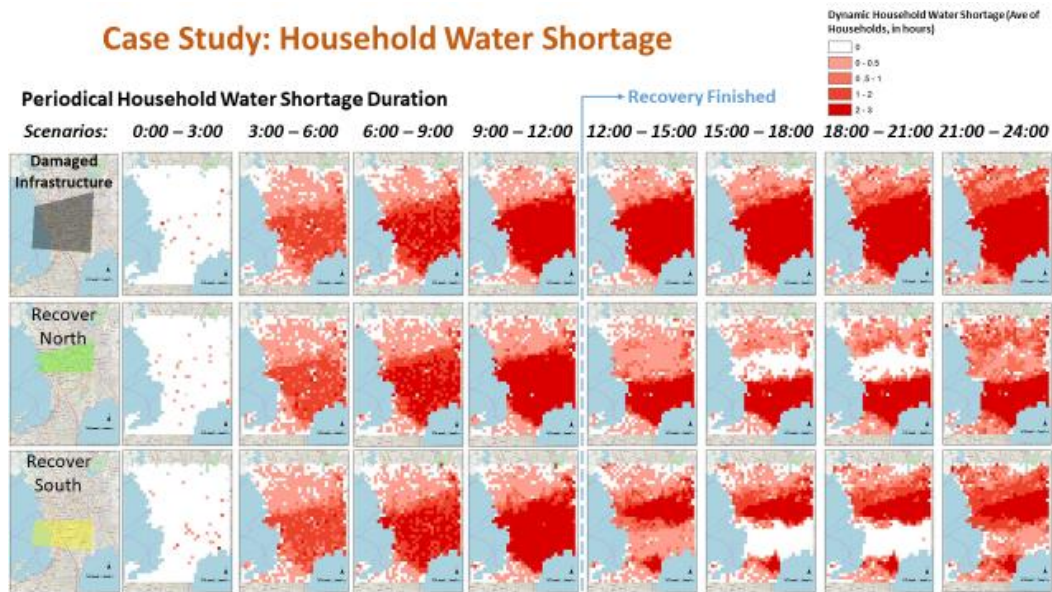
2.7.8 Model insight

This model presents the evolvement of the urban system conditions under disruptions, both temporally and spatially. By observing the model results, the decision makers can choose to intervene in the failure propagation by repairing appropriate infrastructures at the appropriate time point. Further, the repair decision can also be input to simulate the estimated repair effect, which provides more possibility to assist the urban system recovery process.

3 Lessons Learned at Enterprise Challenge 19

In 2019, Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) personnel were invited to Enterprise Challenge 2019 (EC19) in Fort Huachuca to demonstrate FICUS capabilities to the intelligence community. In addition, officers from the 351st Civil Affairs Command joined the exercise to view FICUS and other technologies in action. Over the span of the two-week trials, the FICUS capabilities described in this tech report were demonstrated to and used by intelligence officers and enlisted personnel with discussion on FICUS's utility to the typical missions and responsibilities of Intelligence Soldiers.

3.1 Lessons learned

Review of EC19 feedback showed that the FICUS capabilities offered unique and valuable technologies to the intelligence community by offering more advanced civil-military operational analytics as well as better integrated S9 to S2 and S3 HQ functions during multidomain operations in hybrid warfare. Half of the reviewing Soldiers believed that FICUS's Combat Infrastructural Analysis tools were "paradigm shifting" in improving course-of-action analysis, even when the fog of war is reducing situational awareness. Soldiers reported that the FICUS capabilities could be taught in less than two weeks to typical intel analysts.

Key take-aways

1. Half of reviewing Soldiers thought FICUS would be effective at divisions and above, while the other half believed capabilities could be taken advantage of at the brigade combat team (BCT) unit level.
2. FICUS needs to improve stand-alone capability when operating in disconnected environments.
3. EC19 confirmed the ERDC-Information Technology Laboratory's (ITL) hypothesis that analytic frameworks do not update quick enough during extended conflict to be useful for IPB. Updates need to come from both changing information only available to the IC as well as changing information only available to division or BCT headquarters (HQ).
4. FICUS can interoperate easily with Distributed Common Ground System—Army (DCGS-A).

3.2 Objectives and results

Objective #1: Collect baseline information from Soldiers about existing methods, data, and tools for PMESII/ASCOPE IPB capabilities.

Results and Accomplishments: Successfully Achieved, FICUS team members learned, in detail, the IC's iterative analytic framework cycle (AFC) from analytic frameworks to IPB to course-of-action analyses to observing results back to analytic frameworks (Figure 36).

Program Impacts and Next Steps: FICUS has adjusted the FY19 summer research agenda to better align with improving the AFC. The FICUS team has put together a research proposal in collaboration with Army Reserve Civil Affairs to solicit research funding in this area.

Discussion/Amplifying Comments: Thanks to multiple discussions with US Army Intelligence Center of Excellence (ICOE) experts, as well as officers and Soldiers tasked with reviewing EC19 demonstrations, FICUS team members learned beyond training manuals how HQ units create and deploy IPB. Since FICUS capabilities can enhance analytic frameworks and IPB, this additional knowledge will better align future research with Army needs.

Figure 36. Analytic framework cycle with FICUS
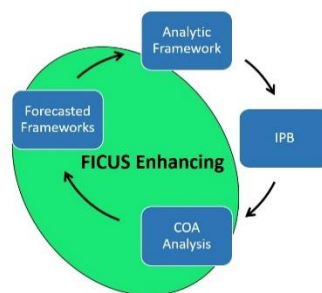
Objective #2: Demonstrate the capabilities of the FICUS system-of-systems modeling environment.

Results and Accomplishments: Successfully Achieved, IC officers and Soldiers provided valuable feedback on the system-of-systems modeling environment, which forecasts infrastructure impacts on social groups in conflict zones.

Program Impacts and Next Steps: Articulating and demonstrating FICUS capabilities remains a time-consuming endeavor. FICUS will create more easy-to-understand content explaining capabilities and potential.

Discussion/Amplifying Comments: FICUS relies on advanced geotemporal analysis and visualization tools not used in government off-the-shelf (GOTS) and other commercial software systems. FICUS's system-of-systems modeling approach is only now being fully researched in the engineering disciplines. FICUS also provides risk assessment techniques only taught and debated in financial and statistical disciplines not associated with geotemporal analysis. This combination of capabilities results in most experts not educated in the other disciplines' techniques.

Objective #3: Demonstrate to IPB creators how to interact with FICUS-UI.

Results and Accomplishments: Successfully Achieved, IC officers and Soldiers suggested that the FICUS-UI was easy to use while offering advice to make the risk assessment tools easier to use.

Program Impacts and Next Steps: Based on IC feedback, FICUS team members brainstormed techniques to make risk assessment easier to understand. Proposals for future research and development have tasks included to support this improvement.

Discussion and Amplifying Comments: While Soldiers indicated FICUS-UI would take about two days of training to master, on average, they suggested that fewer user actions to perform risk assessment would benefit operations.

Objective #4: Receive feedback on the utility of the FICUS results and usability of FICUS features.

Results and Accomplishments: Successfully Achieved, IC officers and Soldiers often wrote long reviews of FICUS capabilities and volunteered information after the exercise was formally completed.

Program Impacts and Next Steps: Compared to EC18, EC19 Soldiers and officers provided more quantitatively useful information. FICUS team members have given positive reviews to other teams and

organizations inquiring on whether to participate in future Enterprise Challenges.

4 Way Forward for Integrated Human Geography Computational Models

The current trend towards unplanned, uncontrolled, and underresourced urbanization in many developing countries has exacerbated major crises and conflicts in the last decades. Understanding and leveraging the complex connectivity of physical and human systems in cities offer various tactical military advantages. While many geospatial capabilities provide solid physical representation of burgeoning urban areas, the human system remains an informational capability gap.

FICUS provides a supplementary analytical tool to qualitative analysis to ensure risks associated with civilian-affecting operations are thoroughly analyzed and mitigated. FICUS generates a range of possible representations of the location of every man, woman, and child in an area of interest by combining survey data with digital maps of residential, commercial, and industrial areas; elevations and slope; locations of waterways and roads; and agricultural and natural areas. People are organized into households and each person and household is characterized by attributes, such as age; education level; religion; house construction; and access to water, electricity, sewer, and other attributes associated with urban life. FICUS also provides for the understanding of the impacts to the population and its various cohorts of infrastructure damage to the electric, water, sewer, and other systems in urban environments (Ehlschlaeger et al. 2018).

FICUS allows decision makers to weigh various courses of actions in executing the mission. Since it is completely unclassified, free, and open source, it could be used in various exercises and joint planning with host nations, international organizations, nongovernmental and humanitarian organizations, and other partner organizations. FICUS fills the informational gap in the increasingly complex, system-of-systems urban operating environment, where qualitative analysis alone will prove inadequate or sometimes fatal.

Sergeants, at E-5 to E-7, are expected to provide best- and worst-case scenarios with their analyses. FICUS visualization techniques would be able to provide best- and worst-case scenarios and an estimation of the distribution of information critical to understanding mission success in the Soldiers' provided experiences. FICUS provides unique and valuable

geographic risk analysis capabilities necessary to the US Army. FICUS will likely provide comprehensive geographic risk analysis with the following additions:

1. Complete object modeling system enhancements to FICUS system-of-systems modeling, augmenting urban infrastructure models with regional infrastructure models (uses existing FICUS academic partners).

2. Add simple geographic editing tools to FICUS. Soldiers performing GEOINT, image intelligence (IMINT), HUMINT, OSINT, and signal intelligence (SIGINT) routinely use Google Earth. They indicated adding simple editing tools, like those within Google Earth, to current FICUS capabilities would allow FICUS to completely replace Google Earth with a better, more secure tool, extending Soldiers' capabilities. ArcGIS training and use usually begin at E-5 or E-6. Current FICUS tools under development would reduce the need for ArcGIS, allowing less training to perform similar tasks in a multilocation, collaborative environment. As of 2020, there were 32,000 Soldiers and Civilians throughout the US Military Intelligence Corps, with most of them potentially using FICUS. Dr. Ehlschlaeger estimates that the US Army Military Intelligence (MI) would save a minimum of $10 million/year with these changes while improving the quality of MI products and capabilities. Savings will come from reduced duplication of effort, less training requirements, and increased productivity of Soldiers. (Can use existing FICUS academic partners or ERDC-ITL).

3. Add Wikimapia and National Geospatial Intelligence Agency (NGA) place names components to FICUS. While Wikimapia is crowdsourced, it provides a population-centric description of place names. Military analysts need both population-centric and US authoritative place names to complete their mission. Adding NGA place names and links to the Wikimapia place names data set to FICUS would fill those MI gaps. (Requires cooperation with NGA, can use existing FICUS academic partners or ERDC-ITL).

4. Add Army-specific, multiscale base maps to FICUS user interface. FICUS (and Google Earth) currently relies on server-based, open-source, multiscale base maps. For maximum use and access, FICUS needs to integrate higher-quality, military, multiscale base maps that can be stored locally on analysts' computers. Seven years ago, ERDC-ITL had an effort to provide a Google Earth Enterprise solution for Army-specific, multiscale base maps. Having a FICUS component with a similar data set would allow for all Soldiers, especially IMINT specialists, to better perform MI whether they currently have access to high-bandwidth internet or not. (Requires cooperation with ERDC-ITL and uses existing FICUS academic partners).

5. Tactical Ground Reporting System (TIGR) should be considered as the tool to bring ground truth data into FICUS.

5 Conclusion

This section discusses theoretical issues of resilience and computational tools necessary to move from traditional risk analysis techniques to quantitative resilience modeling. FICUS, designed as space-time model integrating environment, provides some of the tools to enable quantitative resilience modeling.

5.1 Traditional risk analysis versus resilience modeling

Quantitative risk analysis must account for the impact of all hazards, how vulnerable a system is, and the consequences of the disruptions, known as Hazard × vulnerability × consequence (HVC). Fox-Lent and Linkov (2018) describes multiple limitations to the HVC process. First, HVC is threat specific, unable to account for rare or compounding threats. HVC is not very useful during rare events such as severe storms or military conflicts as data is often not available for calibrating and verifying simulation models. Second, HVC lacks temporal representation, preventing a resilience modeling paradigm that illuminates recovery issues after a disaster. (See Section 5.2, which discusses the resilience paradigm in detail). Third, the HVC methodology does not account for second- or third-order effects. (See demographic and infrastructure modeling efforts earlier in this tech report to see examples modeling second-order effects).

We believe resilience is a better paradigm than risk analysis to manage the quality of a system. According to the National Research Council (2012, 16), resilience is "the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events."

Defining resilience to a system requires explicit modeling over time. Figure 37 illustrates the effectiveness of a system over time. Typically, a major disruption will decrease the system effectiveness. The recovery phase begins after disruption impacts occurs.

Figure 37. System performance over the event cycle.
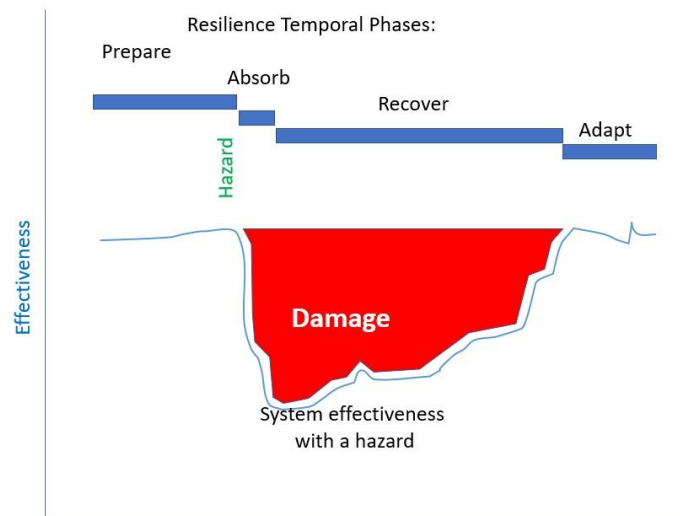
5.2 The resilience matrix

Linkov et al. (2014) designed the resilience matrix "to explicitly capture the capacity of a system across the timeline of a disruptive event" (Fox-Lent and Linkov 2018, 32). They used a network-centric operations doctrine (Alberts and Hayes 2003), which divided networked systems into four domains: the **physical domain**, mainly the system infrastructure and equipment; the **information domain**, the information systems about the physical systems; the **cognitive domain**, mainly decision-making processes informed by the information domain; and finally, the **social domain**, the human resources supporting the entire system. The physical domain is usually the only domain explicitly modeled in most disaster-relief risk analysis models. The information domain includes the information systems discussed in this report as well as the sensor information, "demographic or behavioral information about the social domain, and methods for both gathering and sharing data in real time" (Fox-Lent and Linkov 2018, 33). FICUS research places more effort in modeling the general population at large to ensure all second-order effects of population impacts are applied to the physical and information domains.

With the command-and-control domains as rows of a matrix, the temporal phases of resilience are the columns of the resilience matrix: prepare, absorb, recover, and adapt—based on the National Research Council's (2012) definition of resilience. The full resilience matrix is shown in Figure 38.

Figure 38. Overview of resilience matrix with the event cycle as the columns and system domains as the rows, with research gaps encircled.

To describe the full system over time, the resulting resilience assessment system should be populated with performance metrics in each of the 16 cells and should be capable of providing those metrics during a conflict or disaster. However, most existing scientific and engineering simulation models and analytics operate within the plan and prepare and absorb phases and mainly represent the physical and information domains (the orange rectangle in Figure 38).

The earlier discussions in this technical report on the SWEAT-MSO or PMESII/ASCOPE frameworks can also be applied to the resilience matrix. As the SWEAT-MSO framework provides a foundational taxonomy organizing information for military engineer decision makers and the PMESII/ASCOPE's taxonomy supports military operations, quantitative models supporting the understanding of resilience would populate cells in the resilience matrix, giving installation planners a more wholistic perspective of the challenges they may face across potential disruptive event timelines.

Based on numerous discussions with ERDC experts researching resilience, most metrics and models support situational understanding in the physical and information domains. Unfortunately, explicit models of the cognitive and social domains fall short. It is also believed that explicit modeling of the recovery and adaption resilience phases are much less covered than simulation modeling in the preparation and absorb phases. The need for additional cognitive- and social-domain simulation models and better recovery- and adapt-phase models drives the HGDemo research efforts. For

this reason, much of the HGDemo research focused on providing clarity in space-time modeling to provide more metrics in the recover and adaption phases, advancing demographic models to support the social domain, and advancing 3D and uncertainty visualization techniques to better support the cognitive domain.

Space-time modeling will also assist in the difficult decision between improving the effectiveness of a system vs. improving the resilience of a system. While not always an either/or decision, it can be. Figure 39 demonstrates the tradeoffs.

Figure 39. Improving resilience vs. improving effectiveness.
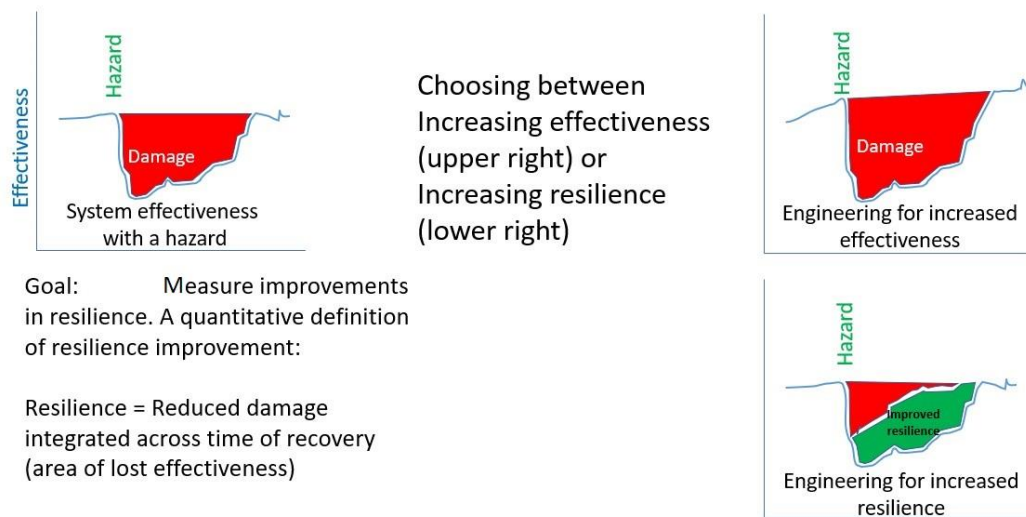
One quantitative metric of a system's resilience could be the accumulated amount of damage for a common hazard. The upper right graph in figure 38 shows how increasing effectiveness without considering resilience might actually reduce resilience as the accumulated damage over time will be greater than the original system. However, engineering for increased resilience might add more value to the installation or community using that system.

5.3 Final thoughts

While the research programs funding FICUS development did not specify resilience enhancement as a goal, FICUS's ability to integrate multiple space-time models to communicate complex interrelationships provides a pathway to effective recovery quantitative modeling. Recovery modeling is currently a high-priority research topic across the United States

government, with many civilian and military gaps identified. FICUS's uncertainty quantification techniques enable accurate, although potentially imprecise, analyses, especially when using social media data, other information from the social domain, and when considering forecasting results through longer time scales.

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Abbreviations

AFC	Analytic framework cycle
ATP	Army Techniques Publication
ASCOPE	Areas, structures, capabilities, organizations, people, and events
BCT	Brigade combat team
CBRN	Chemical, biological, radiological, nuclear
CERL	Construction Engineering Research Laboratory
CMO	Civil-military operations
DCGS-A	Distributed Common Ground System—Army
DigiPops	Digital Populations
DoD	Department of Defense
EC19	Enterprise Challenge 2019
ERDC	Engineer Research and Development Center
FICUS	Framework Incorporating Complex Uncertain Systems
FICUS-UI	Framework Incorporating Complex Uncertain Systems—User Interface
FVBI	Febrile and vector-borne infections
GEOINT	Geospatial intelligence
GOTS	Government off-the-shelf
GRL	Geospatial Research Laboratory
HGDemo	Human Geography Demonstration
HISA	Human-Infrastructure System Assessment

HPC	High performance computing
HQ	Headquarters
HUMINT	Human intelligence
HVC	Hazard × vulnerability × consequence
ICOE	Intelligence Center of Excellence
IDP	Internally displaced persons
IMINT	Image intelligence
IPB	Intelligence preparation of the battlespace
IPUMS	Integrated Public Use Microdata Series
ISIL	Islamic State of Iraq and the Levant
ITL	Information Technology Laboratory
MI	Military intelligence
NBC	Nuclear biological chemical
NGA	National Geospatial Intelligence Agency
OMS	Object Modelling System
OSINT	Open-source intelligence
PBS	Portable Batch System
PMESII	Political, military, economic, social information infrastructure
PMESII (-PT)	Political, military, economic, social information infrastructure (—physical environment time)
PMESII	Political, military, economic, social information infrastructure
SIGINT	Signal intelligence

SME	Subject matter expert
SWEAT-MSO	Sewage, water, electricity, academics, trash, medical, safety, other
TIGR	Tactical Ground Reporting System
TRANSIMS	Transportation Analysis and Simulation
UQ	Uncertainty quantification
US DOT	United States Department of Transportation
USG	United States Government
UTP	Urban Tactic Planner

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14. ABSTRACT

Framework Incorporating Complex Uncertain Systems (FICUS) provides geographic risk analysis capabilities that will dramatically improve military intelligence in locations with the Engineer Research and Development's (ERDC) demographic and infrastructure models built and calibrated. When completed, FICUS would improve intelligence products by incorporating existing tools from the National Geospatial Intelligence Agency, ERDC, and FICUS prototype models, even in places without demographic or infrastructure capabilities. FICUS would support higher-fidelity intelligence analysis of population, environmental, and infrastructure interaction in areas with Human Infrastructure System Assessment (HISA) and urban security models built and calibrated. This technical re-port will demonstrate FICUS prototype tools that allow Civil Affairs Soldiers to provide situational awareness information via a browser inter-face.

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