

# Exploratory Sequential Data Analysis for Multi-Agent Occupancy Simulation Results

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## ABSTRACT

In this paper we apply the principles of Exploratory Sequential Data Analysis (ESDA) to simulation results analysis. We replicate a resource consumption simulation of occupants in a building and analyze the results using an open-source ESDA tool called UberTagger previously only used in the human-computer interaction (HCI) domain. We demonstrate the usefulness of ESDA by applying it to a hotel occupant simulation involving water and energy consumption. We have found that using a system which implements ESDA principles helps practitioners better understand their simulation models, form hypotheses about simulated behavior, more effectively debug simulation code, and more easily communicate their findings to others.

## Author Keywords

Exploratory sequential data analysis; agent-based simulation; multi-agent simulation; occupancy simulation; visual analysis; debugging; tagging; annotation.

## ACM Classification Keywords

I.6.6. [Simulation and Modeling]: Simulation Output Analysis; H.5.2. [Information Interfaces and Presentation]: User Interfaces – Graphical User Interfaces.

## INTRODUCTION

Simulation development is an iterative process typically beginning with model design and programming, followed by the execution of a number of simulations, generating streams of results that may be analyzed. As simulation is based on the advancement of time, simulation results are typically sequences of time series data that are concurrent in simulated time. These parallel time series may be analyzed for scientific purposes, such as the generation and testing of hypotheses about the phenomena under study; design purposes, such as performance evaluation of various design options; or development purposes, such as model debugging. There is hence a need for analysis tools which support these tasks, particularly general-purpose analysis tools applicable to entire classes of simulation models such as those involving numerous agents.

Multi-agent occupant simulations are becoming prevalent in the domain of architecture and building science [1,3,12,16]. These simulations can produce large datasets that are

difficult to analyze and visualize. For example, in case of crowd simulation [19], simulation output is generally shown as an animation of agent movements. In cases where expected behavior is somewhat clear, such as emergency evacuation scenarios, this level of detail is sufficient. However in context of other building occupancy models [1,3,13,16] unexpected occupant behavior is likely to emerge, and thus a greater number of exploratory options are needed at the analysis and visualization stage.

To help practitioners find and debug important behavioral patterns produced by multi-agent simulations, we present an Exploratory Sequential Data Analysis (ESDA) tool called UberTagger [6] that displays aggregate data in the context of agents' positions and other time-varying properties. We demonstrate the system's usefulness by applying it to a hotel occupant simulation involving thermal comfort and energy and water consumption. With an effective system for finding behavioral patterns and tagging them, one can gain insights about a simulation model that might be missed when viewing animations, profiles, or statistics in isolation.

## RELATED WORK

### Exploratory Sequential Data Analysis (ESDA)

Data analytics has been called “detective work” by Tukey [22] to support hypothesis generation. To capture the scope of work done by analysts, a set of principles called Exploratory Sequential Data Analysis (ESDA) was proposed by Sanderson and Fisher [10], originally designed for video analysis of human-computer interaction (HCI) tasks. To better categorize the needed features of analysis tools, the ESDA methodology proposes eight fundamental data transformations critical to support scientific inference and hypothesis generation workflows. The transformations are referred to as Chunks, Comments, Codes, Connections, Comparisons, Computations, Conversions, and Constraints.

### Chunks (Groups)

Chunks are “segments of adjacent data elements that the analyst perceives as forming a coherent group” [10]. Grouping and segmentation of data is one of the most fundamental analytical operations that allows the analyst to observe differences and similarities between or within subsets of the data. It is also sometimes becomes necessary to support hierarchical grouping, where groups can be further grouped.

### Comments

Comments are “unstructured informal or formal notes that the analyst attaches to data elements, to groups, or even to the results of intermediate analyses” [10]. Comments help to document steps taken during the analysis, which leads to richer data provenance information. Also, in the context of group projects, the ability to add comments helps analysts communicate observations to other members of their team. This has been shown to help emergent patterns to be more easily discovered [15].

### Codes (Tags)

Codes, or tags, are user-defined names “attached to data elements or chunks designed to capture the meaning of the data while reducing the variability of its vocabulary” [10]. A tag may be just one word, or a phrase, where each word is separated by either a dash or an underscore. The ability to add tags aside from just comments adds rich metadata that helps analysts more consistently and accurately classify evidence and establish common ground [24], as well as adding a useful organizational mechanism that has been shown to improve overall data analysis results [24].

### Connections (Links)

Connections are “a means of following threads through their nonlinear paths and identifying the relationship among their elements” [10]. Connections, or links can also express linear, temporal, or implicit relationships in the data, or relationships between different types of data. Support of links in an analysis process have also been shown to help to gather scattered evidence to support a hypothesis generation process [24].

### Comparisons

Comparisons “demonstrate the effects of different treatments of the data with one another” [10]. For example, one might compare different runs of the simulation to identify effects of the different input parameters. Or on the occupant level, one may compare behavior of different occupants and try to discover anomalies or gain a greater understanding of space utilization.

### Computations (Aggregation Functions)

Computations “reduce the data to summary representations, including simple counts, complex quantitative relationships, or tests of statistical significance” [10]. While visual-analytics offers a rich analytical foundation, coupling it with quantitative statistical analysis lets the analyst be more confident in the statistical significance of their observations. Aggregating data in this manner promotes the use of informal observation in rigorous scientific approaches.

### Conversions

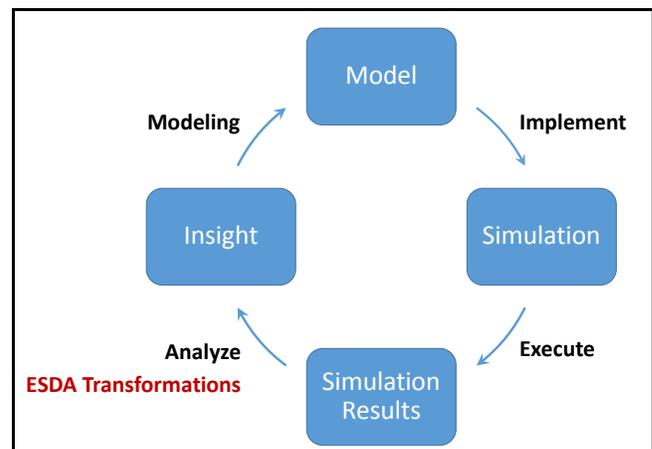
Conversions “transform data in order to reveal new patterns” [10]. Often, conversions are visual, such as in cases of using a new visualization, for example plotting a time series data in a line chart. However, conversions can

be more numeric or procedural, such as changing units, converting to a new coding scheme, or changing the scale of analysis.

### Constraints (Filters)

Constraints are filters applied to data to exclude items or to select specific items. For example, an analyst may want to focus on a certain subset of the data, such as only a particular group of occupants or a specific period of time.

In the context of the overall modeling and simulation cycle [2], ESDA falls within the Analysis phase, where the analyst tries to gain insight from the simulation results (see Figure 1). Traditionally this phase is associated with testing the validity of the model, quantifying uncertainty in the results, verifying the correctness of the simulation code, and improving performance.



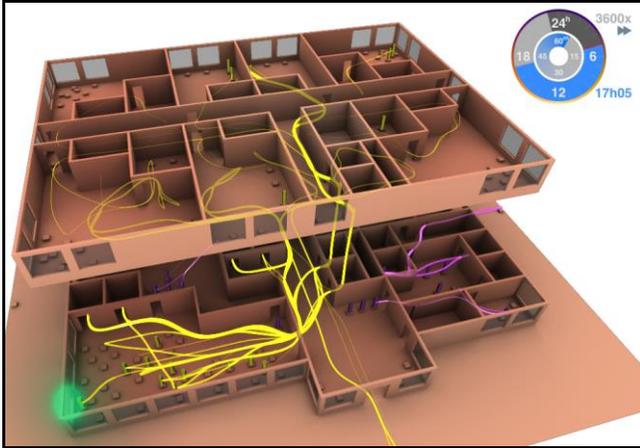
**Figure 1: Modeling and Simulation Cycle [2].** Arrows represent processes and boxes represent outcomes.

### Occupant Simulation

To produce the input dataset for our exploration, we replicate a resource consumption simulation of occupants in a hotel building described in Goldstein et al. [13]. At any given time the hotel may be occupied by a number of employees and guests. The simulation tracks the position of each simulated occupant, their activities such as eating, sleeping, and rates of power and water usage for all activities. It also predicts air temperatures, which varies smoothly over the interior of the hotel and changes gradually over time.

The output of this simulation has been previously visualized in [4], as shown in Figure 2, where occupant paths are animated using streamlines communicating overall space utilization. Such visualizations encompass some of the ESDA Transformations. For example, visualizing the occupant path is an example of a *Conversion*, while using different colors for hotel guests (yellow) and employees (purple), is an example of *Chunks*. However, many of the ESDA Transformations are missing, such as *Comments* and *Codes*. Similarly, other work in occupant simulation output

analysis [11,17,20,21], may implement some of the ESDA Transformations, but may leave out some important aspects as they may not be as relevant in the particular evaluation. In this paper, we try to present a system that incorporates all of the ESDA Transformations to illustrate the potential use of these techniques in future work on simulated occupant behavior analysis.



**Figure 2: 3D Floor plan of the Hotel Building from [4]. Yellow paths are hotel guest, while purple are hotel employees, green flash indicates a window opening event.**

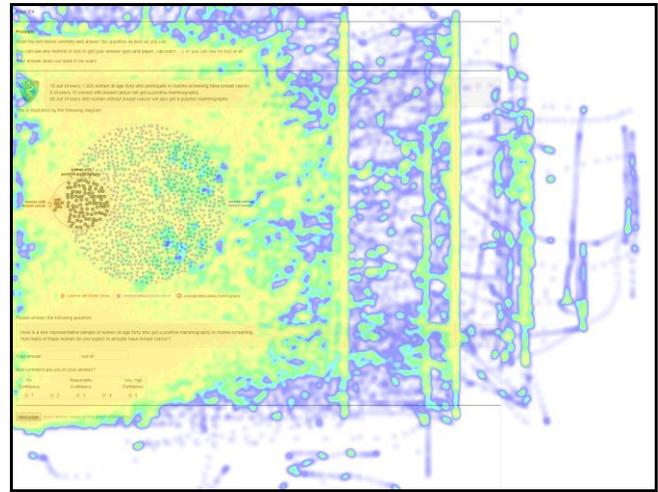
### Visual Analysis in HCI

To apply ESDA to the domain of occupant simulation, we draw on work done in the field of human-computer interaction (HCI), as that was the original source of the ESDA theory [10]. Developments in the visual analytics field may be applied to many systems for the analysis of complex datasets [5,6,8,14]. Specifically, we observe a similarity between the building visualization in Figure 2 and visualizations that depict user interaction data (mouse movements) as a Heat Map in Figure 3. The user interaction visualization shows the aggregate behavior of many participants of an online survey, providing information about the amount of time spent in a given area of the web page. This maps well to the building design domain, where space utilization is of great concern.

To perform our data exploration, we use UberTagger [6], an open source ESDA tool that was designed for analyzing user interaction data. In the next section we outline UberTagger’s user interface, and explain how it supports analyses of not only user interaction data but also multi-agent occupant simulation results.

### APPLICATION OF UBERTAGGER

The user interface of UberTagger is shown in Figure 4 with panels labeled A through I. Here we describe each panel with a focus on its use of building occupant data and its association with the eight fundamental data transforms of ESDA.



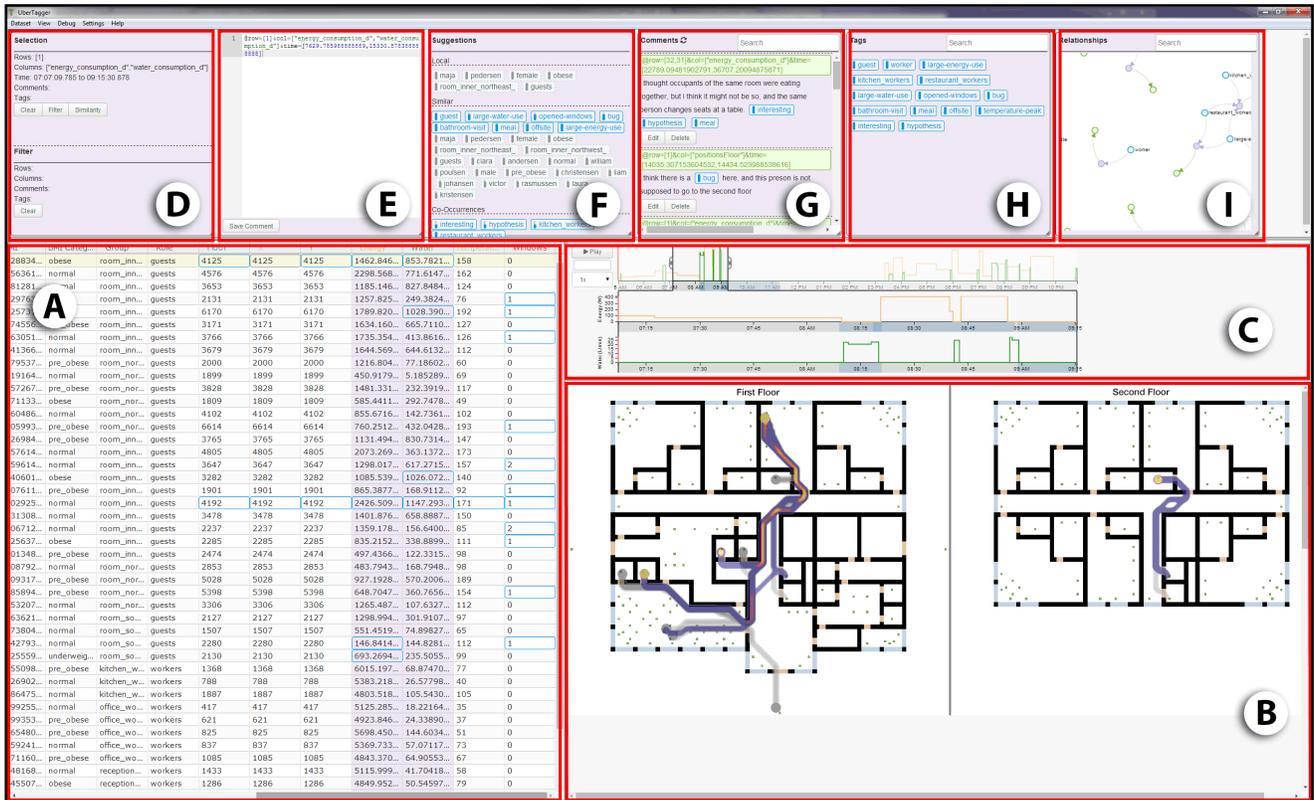
**Figure 3: Heatmap of Mouse Movements from [5] showing large interaction patterns, such as the evidence of scrolling in different window sizes (evident by several vertical striped groups of movements in the right side of the image.)**

### Data Grid Panel

The Data Grid Panel (see Figure 4A) is a traditional data table widget, similar to the table interface found in general purpose tools such as Microsoft Excel [18]. To map the data into the Data Grid, we take an occupant centric approach, where each row of the table represents a single occupant, and each column represents some variable associated with that occupant. These column-specific variables may be input parameters or aggregations of time series data.

To make the population of the hotel more realistic, a number of demographic parameters are used as input into the hotel model simulation [13], specifically name, age, gender, height, weight, Body Mass Index, and smoking habit. These parameters are generated procedurally using statistical averages from number of sources, such as the CIA World Factbook [9], NationMaster.com [25], the and World Health Organization BMI Database [26]. Two other very important input parameters for each occupant are the role and group membership. The role parameter determines if a given occupant is a guest or an employee, and a group parameter indicates (a) which room they are staying in the case of a guest, or (b) what job they are performing in case of an employee. Each parameter is displayed in a different column of the Data Grid.

The time series data that we take advantage of in this view include the following: the occupant’s position (floor, and x, y coordinates), his/her water and energy consumption, and his/her window opening actions. In order to map time series data into the Data Grid, an aggregation function needs to be defined for each time-series type. For example, for window opening events, we use summation, while for water consumption we perform an integration to find the total number of liters consumed by an individual. When a given



**Figure 4: UberTagger Interface. Data Grid (A), Heatmap Floor Plan (B), Line Chart (C), Current Selection (D), New Comment (E), Tag Suggestions (F), Comments (G), Tags (H), Relationships (I)**

cell is selected, the corresponding source time series can be visualized in other panels (e.g. Line Chart, Figure 4C).

In terms of ESDA support, *Chunks* are implemented using a flexible selection and tagging mechanism, where any set of rows or columns can be selected as a group, and saved and tagged. Sorting based on column value implements *Comparisons*, which gives the ability to rank occupants relative to each other. Sorting by similarity allows for ranking based on multiple columns at the same time. See [6] for details related to similarity sorting implemented in UberTagger. The flexible row and column selection is also an example of *Constraints*. As the analyst selects different rows and columns, this selection can serve as the filtering mechanism and may be tagged to be re-used. On top of that, any selection can also become a filter, and selected rows or columns can be hidden from the view to decrease visual complexity of the grid. If a given cell has a corresponding *Comment* or a *Tag (Codes)* it is styled with a blue border.

### Heat Map Panel

The Heat Map Panel (Figure 4B) contains a floor plan of the building design with a heat map of occupant movement overlaid. The hotel design used for our exploration consists of a two-story building, each floor shown side by side in Figure 4B. The hotel features 11 guest rooms, private and public bathrooms, a restaurant, a kitchen, an office, hallways, two elevators, and storage spaces. Waypoints

(green dots) represent places where people perform actions, for example, guests eat and sleep, and employees prepare food and perform office work [13].

The visualization of occupant locations in a form of a Heat Map is a good example of the *Conversions* and *Connections* transforms. Since the occupant’s locations are visualized on top of the building’s floor plan, implicit *Connections* are revealed between occupant-specific behavior and the special layout of the building. The *Conversion* is created when an occupant’s location coordinates are converted into a Heat Map plot, where gradient from purple to yellow indicates increased amount of time spent in that space over selected region of time. Note that “heat” in this case refers to the utilization of space, not temperature. The Heat Map Panel also supports *Constraints* by two mechanisms, first only selected occupants’ paths are visualized, and second, if a time interval is selected, movements that are within the selected interval are colored with a purple to yellow gradient, while movements outside of the time interval are in gray. See Figure 6, for number of example Heat Maps with different occupants and time intervals selected.

### Line Chart Panel

The Line Chart Panel (Figure 4C) visualizes time series data that has been selected. Whenever the analyst selects a time series by clicking on a column in the Data Grid or interacting with various menus associated with the Tags and

Comments panels (Figure 4F-I) a line graph corresponding to all the selected time series is plotted. The colors of each time series are defined as an input parameter for each type of time series. For example, as can be seen in Figure 4C and Figure 7, water consumption rate is in green, and power consumption rate is in orange.

Plotting time series data is an example of *Conversions*, as sequences of time-associated values are arranged on a 2D viewing area. *Comparisons* are supported by plotting multiple selected rows or columns. All selected time series are overlaid in the line chart on the same x-y axis, with the y axis normalized to a 0 to 1 interval. Additionally, all the individual time series are displayed below, with each line chart having its own properly scaled and labeled y-axis. This allows analyst to compare both, different time series for a particular occupant, and same-type time series for different occupants.

To be able to explore some period of time in detail, an analyst can select a time period in the top line chart, and all the line charts below update to only the selected period. This is an example of *Constraints* as well as an implementation of a *Context + Focus* interface [7]. As the selected time interval changes, the Heat Map view of the occupants' movement paths also updates to highlight the space occupied during this time.

The line chart panel also provides a playback feature in the top left corner, with an option of different playback speeds. As the playback is activated, other views can update in response to change of the current time. For example, the Heat Map is updated to show current positions of all the selected occupants.

### Current Selection Panel

The Current Selection Panel (Figure 4D) displays currently selected items, and lets the analyst clear out that selection. There is also a button to update the similarity measure of occupants to a given selection, which is an example of *Comparison* feature. For example, if an analyst selects water and power consumption columns of a particular occupant in the Data Grid, and then clicks the "Similarity" button, the Similarity column (first column of the Data Grid) will update with a distance to the selected item. See [6] for details on how similarity is calculated.

### New Comment Panel

The New Comment Panel (Figure 4E) is the main annotation input interface. Comments are the only annotation content made by users, however, comments can contain any number of tags (*Codes*) and any number of selections (*Connections*).

Tags are simple single-word annotations preceded by a hash sign: "#". Tags may be appear separately or may be embedded in a comment, for example:

This occupant seems to be #lost in the building.

An "@" symbol is used to specify an address or location in the data set. For example, the comment above could specify specific data rows for a specific duration:

The occupant @rows=[27]&time=["07:23:07.986", "07:44:20.833"] seems to be #lost in the building.

Beyond tags and selections, JavaScript code (*Computation, Comparisons, Conversions*) can also be inside of comments. A simple JavaScript API allows analyst to do custom plotting and perform basic statistical analysis. When the comment is added using the "Save Comment" button, the computation is performed and the output is rendered as part of the comment. For example, analyst can include fragment of the line chart, to illustrate her hypothesis, or calculate correlation between different variables to find emergent properties of the simulation. See Figure 5 for an example where correlation is calculated between water and energy consumption of all the occupants.

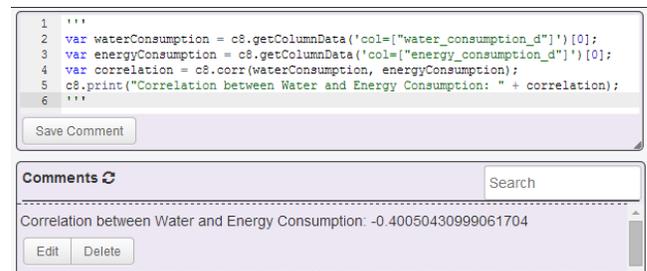


Figure 5: Example Comment that calculates correlation between water and energy consumption.

### Comments Panel

The Comments Panel (Figure 4G) displays the list of existing comments and lets users select comments, edit, and delete them. This view can be filtered (*Constraints*) by entering text inside of the Search field. Part of the search query can be a selection (e.g. @row=[27]), which will show the comments that link to that selection.

### Tags and Tag Suggestions Panel

The Tags Panel (Figure 4H) and Suggestions Panel (Figure 4F) contain tags (*Codes*). The Tags panel contains all the tags previously added to the dataset, which can be filtered (*Constraints*) in a similar manner to the Comments Panel. A number of operations can be performed relative to a given tag, such as inserting it into a current comment or filtering comments, rows, columns, or relationships associated with a given tag.

The Suggestion Panel also contains tags. However, some of them may not have been added to the system by the analyst yet, and are automatically extracted by performing Natural Language Processing on the dataset and looking at similar items to a current selection. These automatically extracted tags appear in gray color, while tags that already have been added by the analyst in the past are in blue. See [6] for more detailed description of UberTagger's Recommender System, which is an example of *Conversion*, where dataset

content is converted into tags, in combination with *Connections*, since by re-using the same tags, implicit connections are created.

### Relationships Panel

The Relationship Panel (Figure 4I) displays relationships (*Connections*) between tags, comments, and selections, where these elements form a directed graph. In practice, users can refer back to these connections to help re-use tags and to informally identify tag frequency in a given dataset.

### ANALYSIS OF RESULTS

To evaluate the usefulness of the ESDA transformations as realized in UberTagger, we explore a dataset produced by a run of the hotel simulation [13], representing 18 hours of simulated time, as previously described in the Occupant Simulation Section.

### Occupant Behavior

Each activity and action of each simulated occupant is determined randomly according to probabilities influenced by their role, the time of day, and comfort level [4]. Grouping occupants based on their role (guest vs. employees) and visualizing each group's location paths in a Heat Map view reveals a difference in space utilization based on the role. While guests tend to only stick to their rooms, hallways and the restaurant (see Figure 6A), employees never go to the guest's rooms (see Figure 6B). A question concerning the lack of cleaning staff in the current hotel model becomes immediately apparent, giving a clear path for future model improvement.

During the exploration of the individual paths in the Heat Map, an unexpected pattern in the model is revealed. Once or twice during the 18 hour period guests would visit rooms they were not staying in, suggesting that a group of friends or colleagues had booked multiple rooms. Strangely, guests would only visit a room directly above or below their own room (See Figure 6C). This turns out to be a known defect in the model where the floor value is not checked. Animations such as the one illustrated in Figure 2 tend to conceal this behavioral pattern, as a viewer cannot easily track the various rooms visited by various occupants. By contrast, the visualizations in UberTagger make the defect obvious. Analysts may tag these suspected issues, and the annotations can help communicate them to other members of the development team. Issues can be marked as *#fixed* in later versions of the model.

From a Heat Map over some period of time (see Figure 6D), one might hypothesize that occupants from the same room are likely to dine together. However by looking at the line chart of water consumption (orange blocks in Figure 6D), it can be observed that the consumption rates appear uncorrelated, leading one to question the coordinated dining hypothesis. Investigating further, the playback feature of the Line Chart reveals that an occupant who was dining alone switched seats for no apparent reason, leaving the

impression that he/she had company. This turns out to be an oversimplification in the model: the agents essentially forget where they had been sitting as soon as they move. As the analyst discovers these behaviors, she adds comments to document the hypotheses generated during her analysis. These comments and tags can be used for future confirmation of any hypothesis, for comparisons, computations, and to build richer connections in the dataset. Later on, she may come back to a dataset, and be able to recount her previous exploration more easily, or communicate her discoveries to her collaborators.

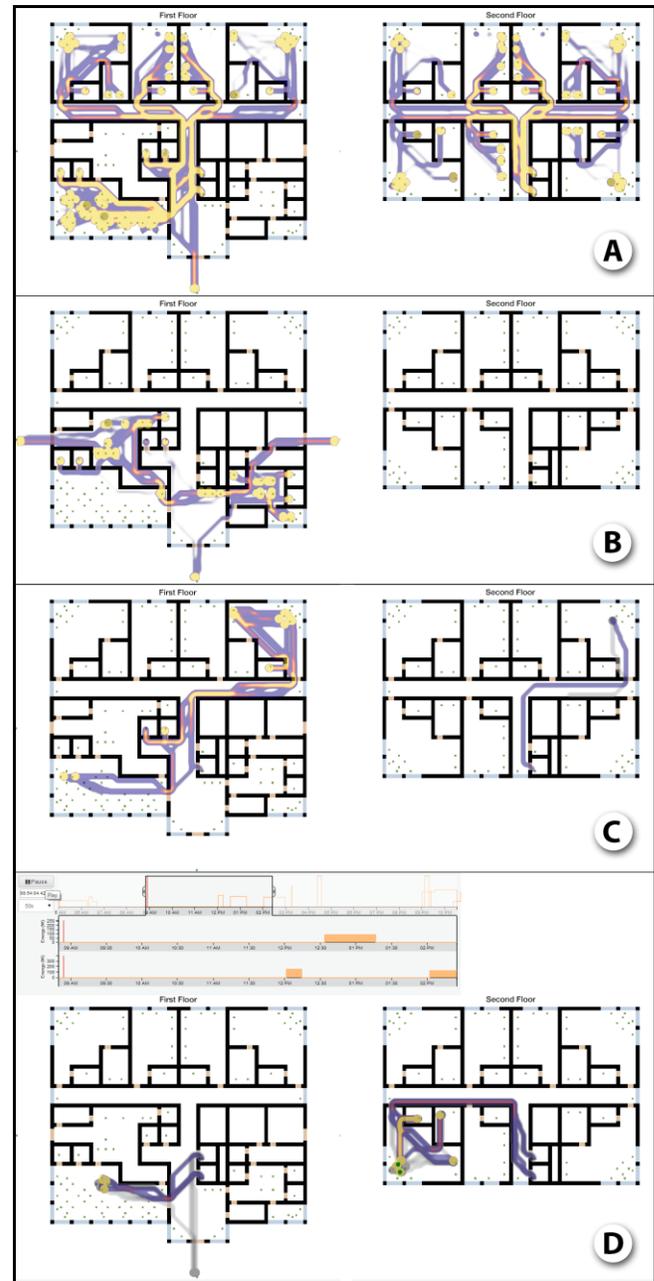


Figure 6: Floor plan Heat Maps revealing behavior patterns.

## Resource Consumption

Sorting occupants based on water usage (Figure 7A) reveals that guests are the top consumers of water. Looking at the distribution of the consumption in the Line Chart also suggests increased usage of the water in the morning. Sorting based on energy consumption (Figure 7B), employees consume more than the guests. Looking at the distribution of the consumption, there is slight hint of the dip in consumption during the night. Seeing these interesting patterns, analysts tag the observations to be more closely explored and confirmed later on.



Figure 7: (A) Water Consumption Rates and (B) Power Consumption Rates.

## CONCLUSION & FUTURE WORK

In this paper we have presented the use of Exploratory Sequential Data Analysis principles to analyze multi-agent simulation results. By combining analysis and annotation tools outlined by ESDA, UberTagger gives simulation users and developers a rich toolbox of analysis features.

All of the ESDA Transforms seem quite useful, especially combining multiple *Conversions* together as in the case of the Data Grid, Heat Map, and Line Chart panels, and filtering them (*Constraints*) based on time regions. Each widget's *Comparison* capabilities (e.g. overlaying time series in the line charts for multiple occupants, and overlaying multiple occupant paths in the Heat Map) stood out as the key to be able to draw conclusions about the data.

*Computations* appear to be useful in later stages of the analysis when hypothesis confirmation is needed and when one must calculate some aggregate values not performed by the default visualizations. The effectiveness of *Comments* and tags (*Codes*) is evident for bug tracking, analysis documentation, and possible collaborative work.

Analyzing the results using ESDA Transforms revealed a number of possible next steps a simulation modeler can take, such as fixing peculiar occupant behaviors or adding cleaning staff to the simulation. Another important avenue to consider is the question of how ESDA exploration can help one distinguish between efficient and wasteful use of water and energy resources.

With respect to UberTagger's user interface, we identified missing features that would be helpful. For example, adding spatial filtering of the Heat Map Panel would allow analysts to draw connections between spatial and temporal behavior, such as use of a particular room or a door. Also, since UberTagger is a generic data exploration tool, it lacks simulation-specific information, such as the internal details of the simulation models, to help investigate deeper relationships between the simulation model and simulation results. Adding more simulation-specific features that appear in the literature [23] may be beneficial.

While we have informally tried to see if the ESDA process enhances collaborative work on a large display (Figure 8), a formal study is needed to evaluate cooperative analysis for simulation development. We note that annotation features have been shown to be quite useful in such scenarios [24].



Figure 8: Two analysts reviewing simulation results on a large 4k screen display where all data values can be shown.

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