Visual Analytics and Experimental Frames

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ABSTRACT

Operational problems often span a wide range of options. In the past, due to computational limitations, the trend was to limit the options set to the minimum number possible. However, with the increase in computational capacity over the last decade, it is now often possible to parametrize the option space instead and simulate hundred or even thousands of options. One of the first attempts in the defence domain was the US Marine Corps Project Albert which looked at data farming in tactical combat modeling. However, simulating vast numbers of options poses new challenges for managing experiments and conducting post-simulation analysis. Some of the model management challenges are which simulations have been conducted, what option space has or has not been explored, which output maps to which input, etc. The analysis problems include considerations such as what model inputs typically lead to what model outputs, whether the results covering a subset of possible options are sufficiently representative for the entire set of possibilities, and how to visualize dependences on the inputs in multi-dimensional problems. This paper focuses on combining the field of visual analytics with modeling and simulation for a, somewhat simplified problem of strategic air lift. Using this problem, that can be summarized as: "what is the force structure requirement for strategic airlift to meet logistics demands of concurrent operations as mandated by the Government of Canada's defense policy Strong, Secure, Engaged?", the paper will look at the management of experimental frames for simulation, option space coverage, and visual analytics applications to the output. Common visualization approaches such as scatterplot matrices, maps, as well as histograms will be exploited to provide an innovative experimentation management and analytics framework.

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INTRODUCTION

Modeling and simulation is being leveraged by many industries and governments to help lower costs and improve efficiencies. The primary method of running simulations is using various computing resources whether they are standalone desktop computers or harnessing the power of the cloud. Even with modern desktop computers a simple simulation can result in an explosion of data. This results in a management problem of what experiments have been conducted with a simulation and what are their results.

Here, we show the use of visual analytics to help manage Experimental Frames for a given case study involving the force structure requirement for strategic airlift. The objective is to meet the logistics demands of concurrent operations as mandated by the Government of Canada's defense policy Strong, Secure, Engaged (National Defence, 2017). We use an extension / application of a previously developed strategic airlift model (Barwell and Wainer, 2020). Here we show the definition of new tools to generate a large amount of data from simulations against the model and aggregating it for use in the commercial visual analytics tool Tableau to help manage Experimental Frames.

Historically, simulations are run, and results are either displayed in custom built visualization tools, or output to tools like Excel for time consuming and complicated analysis. Other side effects of this approach include having to reduce the output down to a manageable set of data or simplify the model to produce conclusions from the simulation. The consumer of these end products is typically different than the person running the simulations or creating the models and requires a method to allow the consumer to easily understand the output obtained from it.

In addition to the results, the consumer also needs to understand the scope which the results represent. Models are typically developed based on experiments conducted against an entity and then run in a simulation against a set of parameters to produce data. These processes define the set of circumstances under which a model is to be subjected to experimentation known as the Experimental Frame (Zeigler, Praehofer, and Kim, 2000). Understanding the Experimental Frame for which the simulation was run allows the consumer to understand how to answer questions such as which experiments have been conducted, what option space has or has not been explored, and which output maps to which input.

This paper will start by covering relevant concepts and related work. We then provide an overview of key supporting features required to connect visual analytics and Experimental Frame management. The visual analytics section will provide an overview of key visual analytics concepts. In the case study section, we will provide a quick overview of the strategic airlift model and then present various visualizations to manage Experimental Frames. We will conclude by discussing future work and concluding remarks.

BACKGROUND

To explore the rapidly changing and unpredictable (Bowden, Pincombe, and Williams, 2015) future security environment requires a model and simulation which can be run with a variety of different inputs. These experiments result in an explosion of Experimental Frames and leads to the management problem discussed in the introduction. The traditional approach to capability acquisition consists in the development of a scenario set that is supposed to represent possible futures and assess capabilities requirements and gaps to address the challenges of this scenario set

(Taylor and Wood, 2004; Taylor, 2017). This approach is based on an implicit assumption that the scenario set is sufficiently representative of all possible futures, i.e., that a solution to this scenario set will be a solution for any of the feasible futures. Intuitively, if the scenarios are selected somewhat randomly, i.e., with no apparent selection bias, this assumption is reasonable. However, even for moderately complex systems, the number of possible scenarios can be large (or even infinite) (Williams and Bowden, 2013).

The complexity of the problem at hand can be the result of a variety of factors working at different scales. In some cases, these factors can be reduced to categorical or quantitative parameters. In such a case, the scenario set can be mapped to a parametric space that can be subjected to further investigation. Dobias and Eisler (Dobias and Eisler, 2018) presented an example of such scenario parametrization for a simple naval force protection scenario. Since the parametric space coverage is easier to express than a discrete scenario space, such parametrization can lend itself to further statistical analysis, and the results can often be expressed as confidence intervals. Furthermore, subject to sufficient computational power, potentially vast numbers of parametrized scenarios could plausibly be investigated.

Among the first defence initiatives intended to build such capability was the US Marine Corps Project Albert, aimed at developing the processes and capabilities of Data Farming in order to be able to examine and understand the landscape of potential simulated outcomes (Horne, 2001). One of the key tools employed by Project Albert was an agent-based model called Map-Aware Non-Uniform Automata (MANA), developed by the New Zealand Defence Technology Agency (Lauren and Stephen, 2002). MANA has been employed to study a variety of military problems ranging from the study of intangibles in combat (Boswell, Curtis, Dortmans, and Tri 2003) to the fractal nature of warfare (Lauren, 2002)(Lauren and Stephen, 2012). Defence Research and Development Canada employed MANA to model crowd control operations; the crowd behavior was parametrized and the use of MANA enabled exploring large numbers of various options (Dobias, Bouayed, Woodill, and Bassindale, 2006). While the use of the parametric models can make generating vast volumes of data relatively simple, the real analytical challenge becomes management, analysis, and presentation of the outcomes across large number of parameters. Whereas one or two-parametric models can be possibly visualized using three dimensional surfaces (Dobias and Eisler, 2018), processing and visualization of multi-dimensional outputs is by far more difficult.

Reviewing the literature for terms such as “management of simulation results”, “experimental frames”, “simulation repository”, and “model repository” produced limited results. The conclusion of numerous searches is that research into visualization of Experimental Frames and Experimental Frame management is limited. During a review of previous and related work the closest field of study which has been explored in a limited fashion is description and management of the models themselves. Rachid Chreyh provides a good overview of these topics in his thesis An Internet-Based Repository for DEVS Models and their Experimental Frames (Chreyh 2009).

Initial model libraries were introduced in the early 2000’s by Bernardi, Filippi, and Santucci to easily enable sharing and re-use of models (Bernardi, Filippi, and Santucci, 2003). The tools were only one aspect required to enable the sharing and re-use of models. Another aspect included a way to describe and provide context for the models. This led to another field of study into how to specify the conditions under which a model is developed or would produce valid results. This work also started in the 2000’s with papers such as Traore and Muzy who described capturing the dual relationship between simulation models and their context (Traoré and Muzy, 2004). These two related research areas were then combined in solutions such as Chreyh’s Internet-Based Repository for DEVS Models and their Experimental Frames. However, Chreyh’s solution is focused on describing and storing the results of experiments and not on management or how to communicate information around experiments themselves.

SUPPORTING FEATURES

The use of visual analytics applied to the strategic airlift problem requires several already developed features and some additional new features. These include:

1. A generic way to express discrete event simulation (DEVS) models regardless of simulator. This allows for each experiment to be expressed in a portable format. We chose to use a previously developed XML format to express coupled models for this.
2. A generic way to express DEVS output regardless of simulator. This allows for the output of each experiment to be expressed in a portable format. We chose to use a previously developed JSON format.

3. Ability to generate and aggregate large amounts of data for a given model. Using a previous microservice architecture we chose to expand upon this by adding a generator and output aggregator. These new programs allow for the quick generation of a large scenario set and the aggregation of data for use in a visual analytics tool.
4. A robust visual analytics tool. Previously modeling and simulation practitioners have relied on custom visualization tools or Excel to explore and report on their simulation output. Using generic tools allows for a bridge between modeling and simulation and other fields like data science. For this paper we chose Tableau as it is one of the industry leading visual analytics tools.

CONNECTION TO VISUAL ANALYTICS

Information visualization is focused on reducing the gap between the data, and the users' mental model of the data (Ji, Youn, Stasko, and Jacko 2007). A mental model is an internal representation of how something in the world works (Staggers and Norcio, 1993). Wherever there is distance between the presentation of the data and our understanding of the data, mental work must be done so that understanding is possible. This type of mental work does not bring us closer to solving domain goals, but rather is a sort of unfortunate precursor for the really important work, and therefore should be avoided wherever possible (Paas, Renkl, and Sweller, 2003). Fortunately, the physical environment can be used to store information, which allows us to “off-load” mental work onto the environment (Wilson, 2002). Visualizations are essentially one way of effectively leveraging this property of the environment to aid thought.

We can use visual analytics to better manage the large volume of Experimental Frames that simulations use. Visual analytics can be used on the input side of a model to determine what has already been produced and it can also be used on the output side to show which inputs connect to which outputs. It can also be used in the more traditional sense to try and find knowledge from the outputs so that practitioners aren’t required to make choices about what data to include or not include from their simulation results.

Colin Ware is an expert in Information Visualization and his book Information Visualization: Perception for Design (Ware 2013) provides an in-depth overview of many fundamental visualization concepts. As discussed in the book it is not possible to provide hard and fast rules for designing and evaluating visualization as it is a complex task. In this paper we decided to focus on the following visualization concepts as they are easily understood by most audiences and common among many modern visualizations. Employing these concepts help users understand the model and results in addition to the experiments which are conducted.

1. Interactivity – Most modern visualizations rely on interactivity to allow the exploration of large datasets in real time.
2. Color – Can easily be used to denote different experiments, however this approach needs to be moderated as color blind individuals could have issues seeing the same data.
3. Glyphs – A glyph is an elemental symbol within an agreed set of symbols, intended to represent a specific piece of knowledge. These can be a powerful tool to communicate a large amount of information, however the set of symbols needs to be known by the user before use.
4. Selection / Filtering – This factor is important as it allows the viewer to explore the data at their own pace.
5. Motion – Does the visualization allow you to quickly find the information you are looking for.

CASE STUDY: STRATEGIC AIRLIFT

Strategic airlift is defined as the ability to rapidly transport a large number of passengers and/or over-sized heavy cargo over long distances within Canada or between Canada and a theatre of operations (Public Works and Government Services Canada, 2020). In 2017, the Government of Canada articulated the tasks it wants the military to conduct and how often it wants the military to conduct those tasks (National Defence, 2017). This resulted in many questions about whether the Canadian military has enough people and resource to accomplish their missions. Using the assumption that there are enough people and resources to conduct concurrent operations, the questions then expand into the area of strategic airlift and whether Canada could sustain the supply chains required for these missions.

Exploration of this question results in many “what if” scenarios. For example, what if more aircraft are added to the scenario to help transport pallets, what if more intermediate logistics support bases are added, what if an operation requires twice the number of pallets, etc. These are just some of the questions that can be explore using this model, however it also creates another issue of managing all the experiments already conducted against the model, or that the user wants to conduct against the model.

This section will introduce the applications of visual analytics to Experimental Frame management from the input and output perspective using the strategic airlift problem. This will be illustrated using the following questions:

1. What options space has been explored?
2. How long does it take pallets to be delivered across various scenarios?
3. What happens when more intermediate stops are added?

Model Overview

The strategic airlift model was defined in previous work (Barwell, and Wainer, 2020) and an overview is provided in this section. The design includes two DEVS atomic models, a location model, and an aircraft model. These atomic models can be combined as shown in figure 1. Any number of locations can be defined and serviced by any number of aircraft. The primary output of the model is the amount of time required to transport a pre-defined number of pallets from location A to location B.

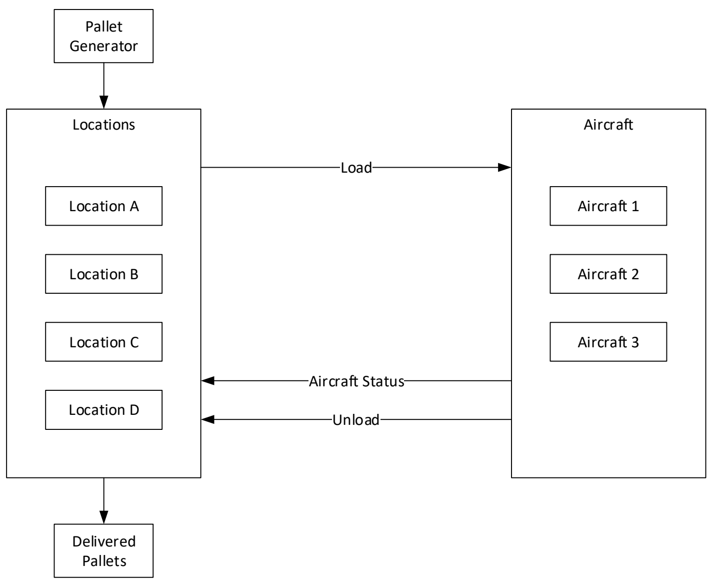

Figure 1. Coupled Strategic Airlift Model

The model begins by receiving a pallet at a given location. A pallet is used to represent a collection of people or goods that require transportation on an aircraft. A pallet is the smallest unit of representation in the model, and an aircraft can carry a fixed number of pallets together. Each location keeps track of which aircraft are available at that point in time. The aircraft then waits for a load to be ready for transport from the location. The location waits until it receives enough pallets to fill at least half the aircraft. Once a location has enough pallets, it groups them together and produces a load to be transported to another location and dispatches it to a waiting aircraft. The waiting aircraft then flies the load to a destination location and announces it has arrived. After the aircraft arrives, it unloads all pallets to the destination. At the destination location the pallets are either delivered if they are at the final location or added to the waiting pallet queue. Pallets wait in the queue until there is an aircraft available to transport them to the next location.

The following assumptions were made: pallets will each have a size of 1 and can be shipped with any other pallet; each location has infinite ability to store and process pallets; to reduce model complexity aircraft are serviceable and available at all times; aircraft fly directly between two locations. The airspeed for each aircraft can be reduced to account for non-straight line routing to avoid diplomatic airspace boundaries, and account for other factors such as weather. Pallets are prioritized by pallet id and there is enough fuel to fly directly from any two points provided by the user in the scenario. The smallest granularity of time required by the model is every minute. While somewhat artificial, these assumptions enabled the development of a relatively simple model and consequently we could focus on the framework management and visualization.

Simulation Overview and Data

An extension to the original strategic airlift simulator was required to generate a large volume of data quickly. This was accomplished by building upon the microservices ecosystem with REST APIs from the original simulator. A generator service and a log conversion service were added. Several of the original microservices were also required to support the process. The goal of this research path is the eventual application of Experimental Frame management to any DEVS model. The following list is an overview of the microservices:

1. Generator – Used to vary the inputs of the strategic airlift simulator to create different scenarios. The user can specify options to varying the number of scenarios produced, the number of locations in each scenario, the initial set of logistical support bases, and the number of planes to use. The output of the generator is an XML file describing the scenario and the scenario input files.
2. XML Translation to Simulator – Using a previously built microservice the XML converter takes the scenario XML and converts it to a simulation system. In this instance the scenario is converted to use the Cadmium simulator.
3. Scenario Execution – Once the scenarios are converted to the simulator format, this microservice runs all the simulations.
4. Conversion of JSON Logs – The strategic airlift simulation was designed to output in JSON. This flexible output format allows for follow on uses in visualizations and other interconnected systems. This microservice extracts the relevant information from the JSON log files and saves it in tab delimited format for use in Tableau.
5. Aggregation of Logs – The output from all the experiments is aggregated together for use in a visual analytics tool.
6. Import to Tableau – Tableau was chosen to explore the data since it is a widely known visual analytics and information visualization tool. Using the JSON open file format allows the user to choose any tool they want from industry tools such as Qlik or PowerBI to custom frameworks such as D3.

The exploration of visualization options required the generation of 5 different scenario sets. Each scenario set consisted of 25 individual scenarios, each with 7 randomly generated locations. Each generated location has a 30% probability of being in South America, Africa, or Asia and 10% probability of being in North America. Each of the 7 randomly generated locations could be defined as a minor operation requiring 200 pallets or a major operation requiring 1000 pallets. When each location is generated it has a 20% probability of being defined as a major operation. The primary bases below and aircraft selection were selected base on proximity to geographic regions to illustrate different visualizations and do not represent real scenarios. The difference for each of the 5 scenario sets are:

Table 1. Overview of Scenarios

Scenario	Primary Bases	Number of C17s	Number of C130s
1	Trenton, Ontario Cologne, Germany	2 0	1 3
2	Trenton, Ontario Cologne, Germany	1 0	2 5
3	Trenton, Ontario Lima, Peru Casablanca, Morocco Kandahar, Afghanistan	3 0 0 0	1 1 1 1
4	Trenton, Ontario Lima, Peru Casablanca, Morocco Kandahar, Afghanistan	3 0 0 0	1 2 2 2
5	Trenton, Ontario Punta Cana, Dominican Republic	3 0	1 1

Scenario	Primary Bases	Number of C17s	Number of C130s
	Tenerife, Spain Ali Al Salem Air Base, Kuwait	0 0	1 1

Option Space

A common question from senior stakeholders when using modeling and simulation for decision support is understanding what option space has been explored or not. Translated to academic terminology it is understanding how many experiments have been run and what were the results of those experiments. This helps the decision makers in their process to understand if they have all the information required to make their decision. Figure 2 shows a map which depicts how long aircraft were waiting on the ground at various locations for pallets in the first scenario set. It also shows how many potential operations were evaluated using this model.

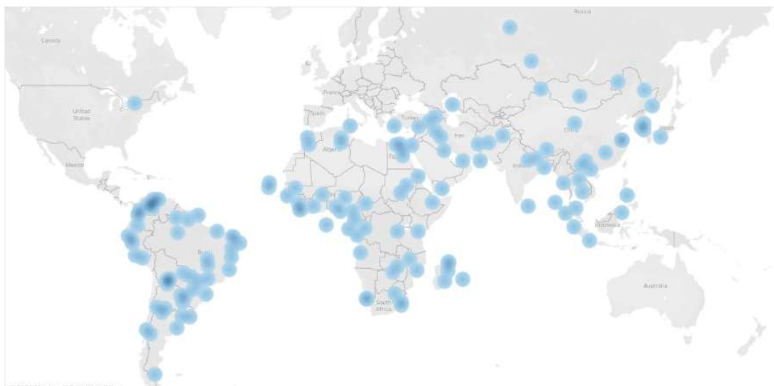

Figure 2. Waiting Aircraft Across Experiments

The primary mental model for the user in this problem space is understanding how many locations were evaluated during the experiments. The primary data points were location based and a map was chosen as the best representation of this as it most closely aligns with the users' mental model of the problem. Additional information was encoded in the visualization by using gradient colors on each location to emphasis the amount of time an aircraft was waiting at a given location. The user is also able to explore the visualization by zooming into any part of the map and selecting a subset of the data to determine why aircraft might be waiting unnecessarily.

Based on the results shown in figure 2 the following can be observed:

1. The option space for South America, Africa and parts of Asia was explored, however other locations have not yet had simulations run against them.
2. From the model perspective it shows that several aircraft were waiting on the ground at their destination for long periods before returning to their home base for additional pallets. Further discussion would be required to determine if the model needs to be adjusted to have aircraft on the ground for shorter periods of time at the destination airport.
3. Destination locations were observed in places such as China and Russia. This could demonstrate an error with our location selection tool and might require further refinements to the generator to remove locations.

Pallet Delivery

The main goal of the strategic airlift problem is understanding how pallets move from one location to another and how long it takes. Experimenting across the greatest number of scenario sets allows the user to understand where there might be gaps or logistical issues. Generically this can be used by decision makers to understand the main factors (experiment inputs) that effect the results (experiment outputs). Taking the same set of scenario data from above and using a scatter plot matrix can inform the user about various trends with experiments. Each scatter plot in the matrix visualizes the relationship between individual pairs of data. A snapshot of scenarios 10 through 14 was selected for ease of viewing as shown in figure 3.

For example, the scatter plot at the intersection of the scenario_id and pallets variable show how many pallets were generated for a given scenario. This allows the viewer a quick way to see that scenario 13 and 14 had slightly more pallets generated then scenarios 10-13. This knowledge could be used when viewing and interpreting other scatter plots to explain trends and interpretations of the individuals scatter plots.

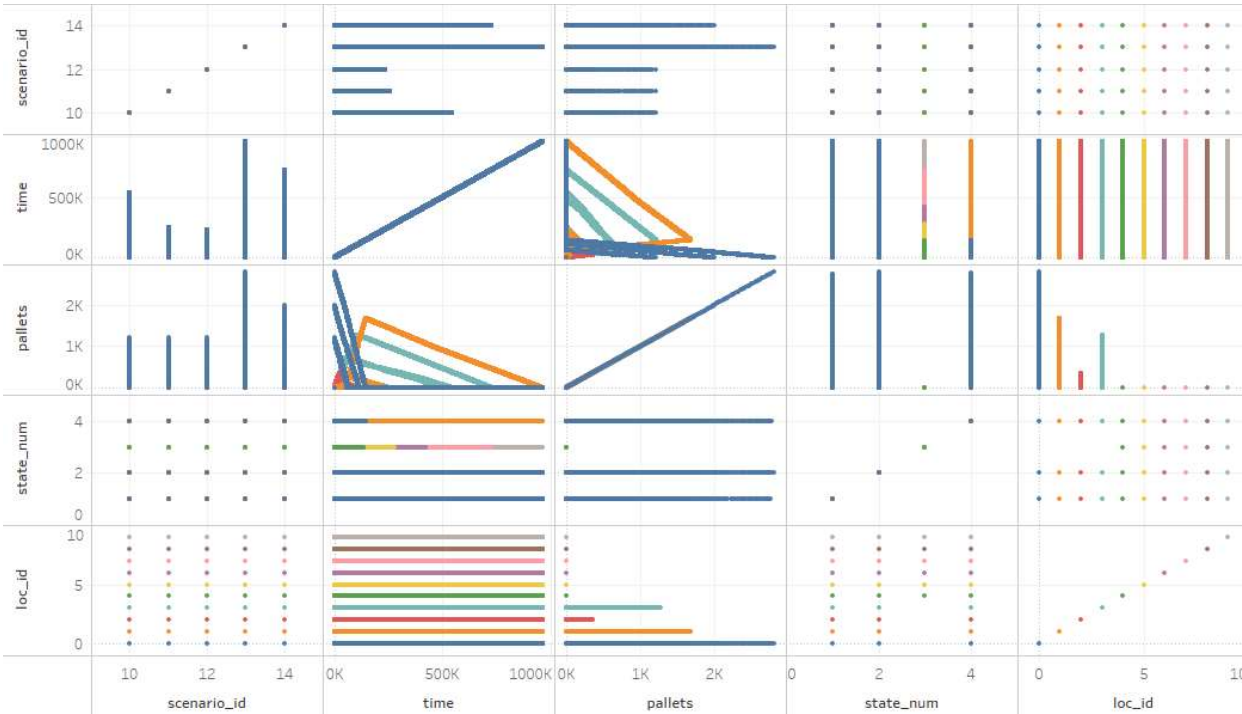

Figure 3. Scatterplot Matrix of Scenario Information

A common issue with multi-variate data is the ability to understand connections between different dimensions. Most simulations have several inputs and outputs and when broken down by each experiment produces a large amount of data. A scatterplot matrix is a common visualization to express the many connections between different dimensions of multi-variate data. When applied to the Experimental Frame management problem it provides the user the ability to understand the connections between inputs and outputs at a macro level. Given the large amount of data points in scatterplot matrices it is helpful to denote different patterns using colors or glyphs. The user can also select specific data points using brushed scatterplots which allow for certain points to maintain their color and everything else to be grayed out.

Figure 3 above shows the simulation state information for scenarios 10 to 14. Each cell represents the intersection between the two dimensions labelled on the axes. Based on Figure 3 the following can be observed:

1. Scenario 12 delivered pallets in significantly less time than other scenarios.
2. Based on the intersection of state number vs time it is shown the experiments may need to be altered to vary the pallet id and location, so pallets don't get shipped to one location at once and effect the results.
3. An interesting trend is shown with pallets vs time where pallets rapidly get transported from the initial location to intermediate bases and remain at the intermediate base for a long time prior to delivery to the destination. This is the result of aircraft configuration for this scenario where C17 aircraft that hold 16 pallets each are used between the initial location and intermediate bases and then switch to C130 aircraft with a 4 pallets capacity each to their destination. Therefore, it would be better for C17 aircraft to augment C130 aircraft at intermediate bases or increase the number of C130 aircraft at intermediate bases to continue the flow of pallets.

Intermediate Stops

The previous visualizations provided examples of how to address the Experimental Frame coverage question and connections between Experimental Frame inputs and outputs, however they did not provide a good visualization to compare the results of Experimental Frames to each other. Building upon the previous pallet delivery question, additional scenarios were developed to illustrate how this would be accomplished using a histogram visualization. Scenario numbers 1 to 5 are described in the Simulation Overview and Data section.

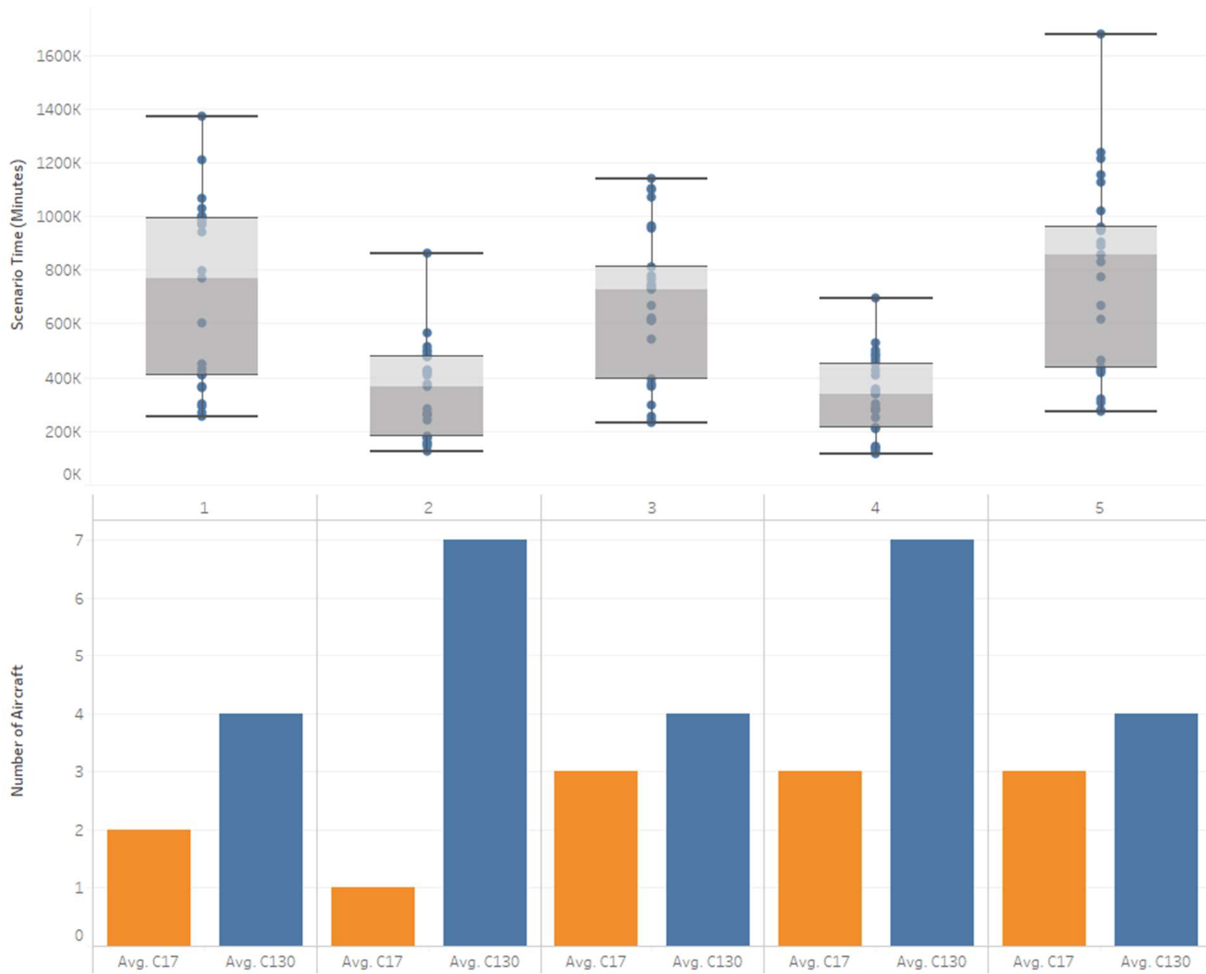

Figure 4. Input / Output Relations

Combining a histogram and bar chart allows the user to quickly see the results of the scenario and the primary input value that was altered between scenarios. A histogram was chosen since it is a common visualization to show the statistical distribution of numerical results. In this case the histogram shows the total time required to deliver all pallets for each experiment in each scenario. Using histograms allow the user to obtain a good understanding of the average times vs the outliers. A bar chart was chosen to show aircraft vs a pie chart as it allows the user an easy way to compare the height of the bars between scenarios. The color also facilitates this by differentiating between the types of aircraft.

Based on the results shown in figure 4 the following can be observed:

1. On average the addition of aircraft reduced the overall scenario time to deliver all the pallets.

2. In scenario sets 2 and 4 the statistical distribution of scenario time is much tighter than the others. This is most likely due to a better allocation of aircraft to ensure pallets continue to flow to their destination and do not wait at intermediate stops.
3. Based on the scenario sets below it also appears that the selection of intermediate stops does not influence the overall scenario time as much as additional aircraft.

CONCLUSION

Using visual analytics to manage Experimental Frames allows the user a way to view and extract knowledge from a large number of data points. This paper demonstrated one option to do this using the strategic airlift problem combined with Tableau to explore several different questions. This was demonstrated using a geographic plot of locations to demonstrate option space coverage. Then using scatterplot matrices to show relationships between scenario sets. Finally, histograms and bar charts were used to show comparisons between different scenarios. This paper demonstrated each question using an individual visualization; however, these can be combined to create an interactive dashboard. No specific workflow was used during the development of this paper as the visualizations were meant as a tool to help answer stakeholder questions based on Experimental Frames.

Using visual analytics reduces the gap between the data and the users' mental model of the data which enables the user to manage an increased number of Experiment Frames together. It also enables data stories that would otherwise be hidden by managing a single Experimental Frame at once to become apparent across multiple Experimental Frames. Finally, visual analytics allows for users to quickly focus their efforts and understand the state of experiments conducted against a simulation and allow them to provide a better overview to stakeholders when confronted with questions such as what option space has been explored. Using visual analytics to manage Experimental Frames will continue to be a growth area given the explosion of computing power and increased use of simulation in industry and society.

FUTURE WORK

This paper presented visual analytics applied to the strategic airlift scenario to manage Experimental Frames. During the development of this paper the following topics were noted for further research:

1. Expanding the work done in this paper to a general application relevant to all DEVS models.
2. Additional research into custom visualizations to better enable Experimental Frame management. This could include improved interactive dashboards with motion and selection / filtering. A user study would be required to see what gaps currently exist and validate any new visualizations.
3. Expand the current model to incorporate additional considerations and more parameters to further push the limits of the visualization.

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