Immersive Analytics for Multi-objective Dynamic Integrated Climate-Economy (DICE) Models

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ISS '16 Companion, November 06-09, 2016, Niagara Falls, ON, Canada
ACM 978-1-4503-4530-9/16/11.
http://dx.doi.org/10.1145/3009939.3009955

Abstract
We are creating an immersive analytics tool for exploring the output of a Dynamic Integrated Climate-Economy (DICE) model, and present early work on the prototype system. DICE models and other Integrated Assessment Models (IAMs) are critical for informing environmental decision making and policy analysis. They often produce complex and multi-layered output, but need to be understood by decision makers who are not experts. We discuss our current and targeted feature set in order to help address this challenge. Additionally, we look ahead to the potential for rigorous evaluation of the system to uncover whether or not it is an improvement over current visualization methods.

Author Keywords
immersive analytics; climate change; integrated assessment; evaluation

ACM Classification Keywords
H.5.1 [Multimedia information systems]: Artificial, augmented, and virtual realities

Introduction
Understanding multidimensional integrated assessment models (IAMs) such as Dynamic Integrated Climate-

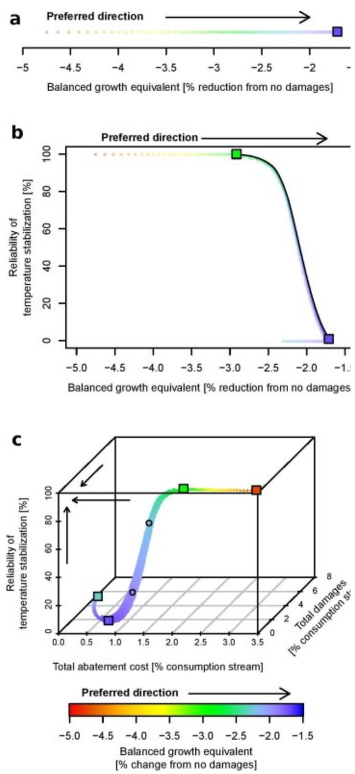

Figure 1: DICE model with one (a), two (b), and four (c) objective variables (dimensions). Multiple objectives adds to model and visualization complexity, but are necessary to model real-world phenomena. Adopted from Garner et al. [11], under their Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/).

Economy (DICE) models can give critical insight into potential future climate scenarios. However, visualizing the output of these models is an ongoing challenge for climate change risk management. Immersive analytics offers a new path to making these models more comprehendible to experts and decision makers. IAMs are tools that combine information from a wide variety of domains (hence, *integrated*) to help understand tradeoffs for complex and uncertain socioeconomic and biophysical processes, such as climate change [13].

However, traditional IAMs often make unrealistic assumptions about stakeholder preferences by collapsing *all* preferences into a single economic utility function. This precludes the analysis of competing preferences among stakeholders, an important aspect in real-world decision making. IAMs therefore need to be multidimensional in order to capture this complexity. This increased model complexity however results in output that is more difficult to interpret, as shown in Figure 1.

Interactive visualization in a climate risk management context is important because decision makers and stakeholders often depend on visualizations for comprehending complex models that frequently contain deep uncertainty. The recent revolution in low-cost immersive VR (iVR) technology opens up new opportunities for intuitive interactive visualizations that we hypothesize will make higher-dimensional IAMs more comprehensible. First we will give an overview of our application area, IAM and climate risk management. Then we will discuss our ongoing implementation of an IAM visualization created by Garner et al. [10] into an iVR context, and look forward to integrating such visualizations into iVR analytical tools.

Integrated Assessment Models

"Effective decision-making to limit climate change and its effects can be informed by a wide range of analytical approaches for evaluating expected risks and benefits, recognizing the importance of governance, ethical dimensions, equity, value judgments, economic assessments and diverse perceptions and responses to risk and uncertainty." according to the Intergovernmental Panel on Climate Change 2014 Synthesis Report [9]. IAMs are one tool for making such decisions [10], but IAMs that analyze the relationship between potential economic and climate change choices often use globally unified utility-based abstractions [21]. This aggregates preferences of stakeholders into one function that assumes a single, ideal rational agent—a highly unrealistic scenario. Different stakeholders often have different or even competing preferences, such as minimizing direct costs versus maximizing mitigation. Methods that collapse user preferences into a single function have created useful insights [17] but simply maximizing the expected utility often does not model real decision-making [2].

IAMs can be difficult to interpret as decision makers must juggle many variables, such as the competing preferences of different stakeholder groups, while attempting to manage and control for real-world consequences. Unsurprisingly, multi-objective decision-making relies on visualizations in a wide variety of contexts [4, 15]. Traditional IAM visualizations tailored to two-dimensional media; while nearly universal, 2D desktop-style interaction has inherent limits. Immersive

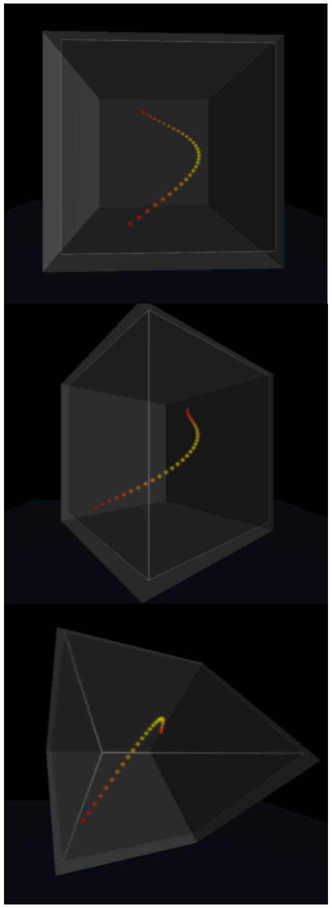

Figure 2: Early graph work utilizing Unity 3D's particle system to create a simple graph with three axes.

interfaces may make complex, multivariate problems easier to understand and their solutions more readily communicable. This is important in a domain where the divergence of two lines on a graph might mean differences of billions of dollars, or thousands of homes. There is a pressing need to make data not only available, but also comprehensible in terms of its real-world implications. iVR enables interfaces that promise to be more effective than traditional methods, and can help to address these challenges.

Immersive Virtual Reality

iVR as an interactive communication medium, is seeing a resurgence in popularity thanks to the entertainment industry, and has important implications for data exploration [6]. Such popularity is exemplified by commercial head-mounted displays (HMDs) such as the Oculus Rift and HTC Vive. iVR research and visual analytics share a common interest in creating intuitive interfaces. Thomas and Cook [20] state, "Visual representations and interaction technologies give users a gateway into their data, letting them see and understand large volumes of information at once. To facilitate analytical reasoning, visual analytics builds on the human mind's ability to understand complex information visually" (pg.11). iVR technology similarly takes advantage of our innate understanding of physical reality within software environments [5]. iVR has been successfully used to understand spatial data [8], such as atmospheric data [12] and showing subsurface phenomena [3]. A notable example of new iVR technology in the realm of visual analytics is work by Moran et al. [16], which demonstrates an integration of a virtual model of a real place with abstract depictions of twitter data.

Visualizing Multidimensional IAMs

Prior work on multidimensional IAM visualization is described fully in Garner et al. [10], but relevant aspects will be reviewed here. We will demonstrate and discuss how accounting for multiple dimensions of preferences changes apparent available optimum decisions, using an existing IAM. This is the Dynamic Integrated Climate-Economy (DICE) model [11, 17], which is one of the models used by the Environmental Protection Agency. Four objectives were employed to represent common (and potentially competing) stakeholder concerns: 1) maximizing expected utility (maximizing cost-benefit), 2) maximizing the reliability of holding global temperature increases to 2°C, 3) minimizing expected damage costs due to climate change, and 4) minimizing the cost of cutting carbon emissions. These objectives are quantified as mathematical functions, which are defined by the decision analyst to represent preferences of the stakeholders, as in [14]. For instance, a stakeholder concerned with keeping global temperatures low might require a function with very high costs for higher temperatures [9].

2D DICE Graphic

Figure 1 illustrates how adding additional objectives clearly changes the optimal set of solutions with three examples (labeled *a, b*, and *c*). In 1(a), the optimum solution is obvious (purple box); since it maximizes efficiency, but given the problem formulation, it assumes that there will always be an increase in global temperature, which in a real context might not be acceptable to some stakeholders. Figure 1(b) adds the objective of maximizing the reliability of temperature stabilization below 2°C, which clearly has an inverse relationship with cost (balanced growth equivalent—see

[10] for explanation). There are two optimal solutions, one for each objective (represented by the teal and blue squares). Figure 1 (c) includes all the variables (three Euclidean dimensions and one of color), and illustrates the complexity of the framed decision making problem with only four variables.

However, there are many limitations to the pseudo-3D depiction seen in Figure 1 (c). For example, it is difficult to judge "Total Damages" values that are located far from another axis. With complex tradeoff curves, occlusion would quickly become an issue, and multiple views would be difficult to distinguish without stereoscopy.

Immersive Visualization of DICE

Though it may be difficult to interpret in 2D, there are advantages to this type of representation that are further enhanced in an immersive context. One potential advantage of using a single multidimensional plot is that complex relationships between variables may be more obvious, since there is not a need to search and mentally associate multiple representations. iVR also has direct benefits for spatial understanding, which is related to immersion [5]. Whether or not

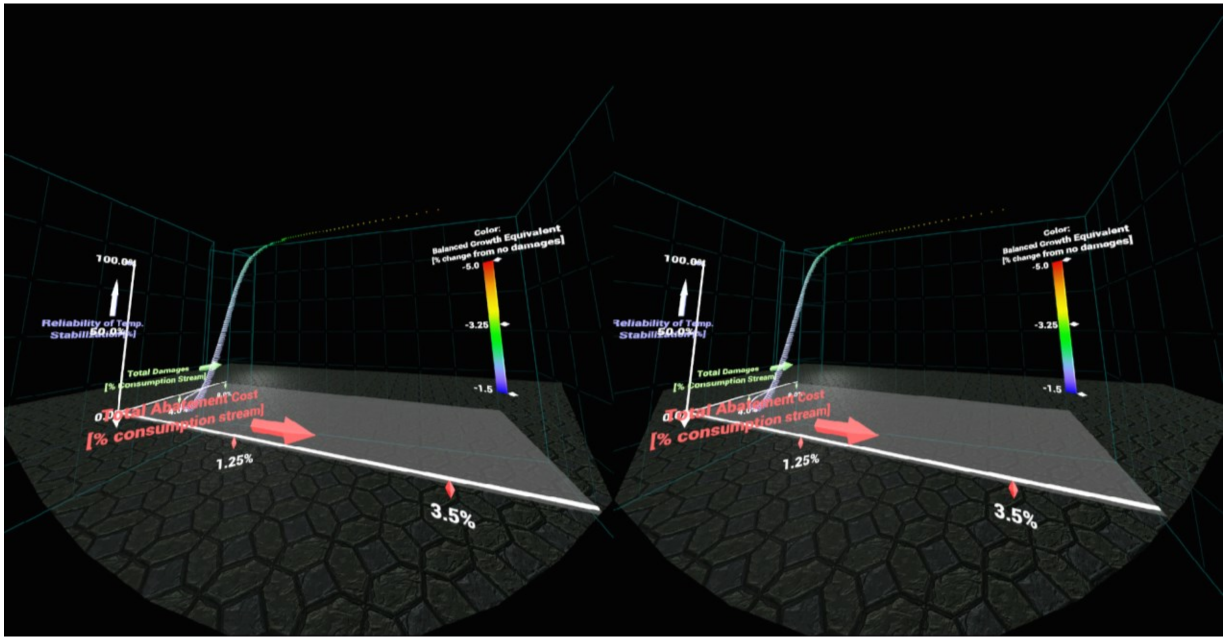

Figure 3: A screenshot of the HTC Vive headset mirror illustrating the current state of the DICE workbench.

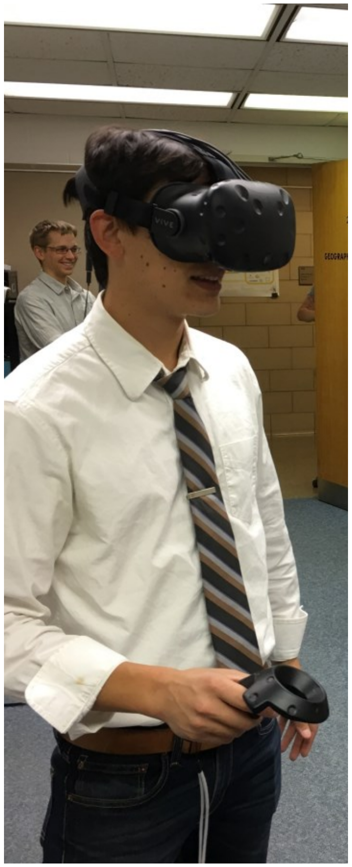

Figure 4: An expert user experiencing our prototype system. This illustrates two main components of the HTC vive hardware: the tethered HMD and the wireless hand controller (only one pictured).

multidimensional iVR representations are advantageous to 2D multidimensional representations (e.g., parallel coordinate plots) in different contexts is an open question, pointing to the need for more evaluation.

Anecdotal evidence points to the importance of detail and scale. One of the authors who is familiar with the 2D depictions of DICE notes that our system made it clear to him for the first time that graphic was composed of points. It also became clear from the *spacing* of the points that the optimization algorithm used on the original data affected dimensions differently, and that the overall shape of the point distribution followed a curve (which was not at all clear in the 2D depictions).

Current Implementation

We have implemented a 3D visualization of the DICE data generated in [10], building from simple 3D graphics shows in Figure 2. In essence, this is a recreation of the cubic diagram in Figure 1 (c).The system uses Unity3D software, a game engine that supports newer generations of HMDs through C# scripting and external libraries. While early prototypes used an Oculus Rift DK2 and a game controller, we have since implemented HTC Vive support. This allows users to explore a room-sized DICE representation in a physical play area.

We have begun to implement basic interaction. The user can pick up and move the DICE representation with the Vive hand controllers. Users can also navigate large distances around the virtual space containing the graph by "teleporting" and change the scale of the graph using the touchpads on the left and right controllers, respectively.

Target Features

There are several specific features that are needed to make this system an effective tool for exploring IAM model output. Users need to be able to select scenarios (points), view the underlying time series data for each of those scenarios (and the inherent uncertainties in the model), and compare them to one another. It must be emphasized that the graphics in Figures 1 and 3 use points that are themselves aggregated summaries of scenarios (model output) of 300 years each [10]. Being able to compare different scenarios is critical in order to find those that both satisfy and balance multiple stakeholder preferences. Additionally, given the assumptions of the model, scenarios that appear valid in summary in aggregate may not be feasible in terms of timescale. An example of this would be a scenario in which investment in abatement is quadrupled over the next three years. This workflow naturally suggests a system that satisfies Shneiderman's Mantra [18].

We plan to accomplish this initially by allowing the user to select points with the Vive hand controllers, and display the related time-series data on 2D "screens" within the virtual environment, that can then be merged as needed. This physical interaction enabled by the controllers is particularly important because it allows the user to interact more intuitively in 3D space.

Development Goals

Our current work is a first step towards implementing a full immersive analytics [6] workbench. Our eventual goal is to fully implement 3D simulations of real-world environments linked to multidimensional (but abstract) data visualizations. Importantly, the user could then view both abstract data visualizations of their results and realistic depictions of what those results would look like in an interactive 3D model of the environment. For example, a planner could see a model of their city being flooded by storm surges of different likelihoods.

Evaluation

iVR is a promising tool for many applications, but critical questions remain over what iVR adds to the decision-making process; what is the value of iVR for decision-making? To answer such questions, we will evaluate our iVR workbench in a decision-making context through a series of controlled experiments. We will examine the role of technology affordances [1] on behavioral intention and perceptions of usefulness [7] for decision-making. Assessment of the role of cognitive style will then be used to identify how well the iVR workbench improves cognitive load in decision-making scenarios with large data sets. Measures related to the use of iVR, presence [19] would also be considered for its role in overall performance with the iVR workbench. The goal of these experiments is to build a framework in which we can identify the value of the iVR workbench for environmental planning scenarios through the technology itself. This framework can be tailored to IAM decision making to provide insights into aspects that iVR generally adds to the decision making process.

Conclusion

Our current work represents first steps towards an immersive analytics tool for exploring IAMs, beginning with the multi-objective DICE model. The output of these models is difficult to interpret despite their utility for helping to understand future climate scenarios. This disconnect between users and their data may be addressed by employing iVR tools and technologies. However, whether or not iVR is useful or superior to traditional desktop paradigms in the domain of environmental decision making is unknown. Therefore, we are carefully considering how to evaluate iVR systems in the context of decision-making.

Acknowledgements

This work was partially supported by the National Science Foundation (NSF) cooperative agreement GEO-1240507 and the Penn State Center for Climate Risk Management and this work was supported by the NSF under IGERT Award #DGE-1144860, Big Data Social Science, and Pennsylvania State University. Funding has also been received through Pennsylvania State University's Institute for Cyber Science. Any conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agencies.

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