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A method to visualize the evolution of multiple interacting spatial systems

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ABSTRACT

Integrated modeling approaches are being increasingly used to simulate the behavior of, and the interaction between, several interdependent systems. They are becoming more and more important in many fields, including, but not being limited to, civil engineering, hydrology and climate impact research. It is beneficial when using these approaches to be able to visualize both, the intermediary and final results of scenario-based analyses that are conducted in both, space and time. This requires appropriate visualization techniques that enable to efficiently navigate between multiple such scenarios. In recent years, several innovative visualization techniques have been developed that allow for such navigation purposes. These techniques, however, are limited to the representation of one system at a time. Improvements are possible with respect to the ability to visualize the results related to multiple scenarios for multiple interdependent spatio-temporal systems. To address this issue, existing multi-scenario navigation techniques based on small multiples and line graphs are extended by multiple system representations and inter-system impact representations. This not only allows to understand the evolution of the systems under consideration but also eases identifying events where one system influences another system significantly. In addition, the concept of selective branching is described that allows to remove otherwise redundant information from the visualization by considering the logical and temporal dependencies between these systems. This visualization technique is applied to a risk assessment methodology that allows to determine how different environmental systems (i.e. precipitation, flooding, and landslides) influence each other as well as how their impact on civil infrastructure affects society. The results of this work are concepts for improved visualization techniques for multiple interacting spatial systems. The successful validation with domain experts of the enhanced small multiples technique proved its usefulness in a use case scenario based on a risk assessment methodology.

1. Introduction

The increasing reliability of environmental models along with the rise in computational capabilities has driven the integration of such models in decision making processes (Jakeman et al., 2011; Hamilton et al., 2015). In order to obtain more consolidated results, it is often necessary to not only simulate the behavior of a system in isolation but rather to compute how it reacts to the inputs of other systems. Applications of this approach can be found in several scientific domains such as climate impact research (Al-Areqi et al., 2014), hydrology (Gregersen et al., 2007) or civil engineering (Hackl et al., 2015). The conceptual and technical considerations of how such coupling can be performed are subject of research in the domain of integrated environmental modeling (Laniak et al., 2013). To facilitate this approach, a multitude of different frameworks have been developed such as the Earth System Modeling Framework (EMSF), the Object Modeling System (OMS) or the System for Environmental and Agricultural Modeling (SEAMLESS) (Granell et al., 2013). Their importance is underlined by the development of standardized communication interfaces such as the Open Modeling Interface (Gregersen et al., 2007) and is driven by initiatives such as INSPIRE (Maue et al., 2011) and the Model Web (Nativi et al., 2013). In disaster risk management of civil infrastructures, for example, such frameworks can be used as processing back-ends allowing to perform simulations in an

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automated way and to enable experts in modifying certain parameters or datasets (e.g., increasing the robustness of a bridge before a flood event). By doing so, it can be examined if this change helps the road network in resisting greater threats and decreases negative consequences due to natural hazards. Changing the conditions of such simulations yields different simulation outcomes each representing an alternative evolution of the systems under consideration from the point in time on this change was introduced. Such alternative developments are referred to as branches (Waser et al., 2010). A typical task is to navigate along these branches in order to explore the development of the simulated system, to compare alternative simulation states and to find means of how to steer the system to a specific state, for example, to minimize damage to buildings (Ribicic et al., 2013). Research in Visual Analytics resulted in several visualization techniques that help the user in navigating through different simulation scenarios (see Fig. 1). Afzal et al. (2011) suggest a line graph based approach with the horizontal axis representing time and the vertical axis representing a certain consequence measure with respect to a baseline scenario (Fig. 1A). Mittelstaedt et al. (2013) use small multiples to depict the evolution for a small section of a spatially distributed power grid (Fig. 1B) and Waser et al. (2010) introduce World Lines, a technique that maps analysis results on visual variables of linear geometries (Fig. 1C). The techniques based on a line graph and on linear geometries are most suitable when dealing with simulations with a high amount of simulated time steps, and therefore, the evolution of the system is best represented in a continuous fashion. The use of small multiples is particularly useful for a smaller amount of time steps, where each state can be represented individually, or when it is sufficient to represent system states at distinct time intervals. World Lines is considered the most compact visualization form of the three.

These techniques, however, are tailored to analyze the evolution of a single system with several branches. None of these approaches addresses the problem of visualizing several systems that evolve in parallel and that interact with each other. Therefore, this paper describes an enhanced visualization and navigation technique that aims at improving the exploration process of multiple simulation scenarios by providing features to represent multiple systems, impacts between systems and enhanced branch representations. This paper is structured as follows: In Section 2, basic terms such as the concepts of model and data dependency are described to characterize integrated models. In Section 3, the requirements for an improved visualization technique are outlined that form the basis for the modified visualization techniques presented in Section 4. In Section 5, an example based on a risk assessment methodology is described on which the visualization method is applied. The resulting visualization is then evaluated in Section 6. Conclusions along with possible future improvements are given in Section 7.

2. Integrated model characteristics

In this section, the basic terms used in this paper including the concepts of *model dependency graphs* and *data dependency graphs* are described, which form the basis for the construction of the proposed technique. In particular, the properties of data dependency graphs are important to depict impacts and branches. A *system* is often defined as a set of related entities or in a similar way (Backlund, 2000). An example for this would be a road network on which vehicles interact with each other and their surroundings. For each point in time, the entities of a system change their properties, such as vehicles changing their positions on the road network. The *state of the system* is therefore comprised of the positions (and potentially other properties) of each of the vehicles. Because it may not be necessary to model such aspects in detail, the system is abstracted. For example, the road network is discretized into distinct segments and only the traffic volume at each segment is taken into account. The state of this system would then be comprised of the traffic volume that is present at each road segment. In the context of this paper, a *system model* (or short *model*) is then used to estimate these states. From a technical point of view, these states are represented by datasets. A *model dependency* exists when one model requires data from another model in order to produce data. This way, models can be coupled, eventually forming networks of dependent models that can be represented as a model dependency graph. Such representations are provided in many integrated modeling and GIS applications as graphical user interfaces that allow to link processes or models. They usually provide general information on the model and process relationships and neglect temporal aspects. Considering temporal dependencies can further refine these representations. In order to produce a dataset for a given point in time, a model may require data with different temporal characteristics. In particular, two cases are considered: A *time-invariant dependency* exists when a model does not require any data from other time steps than the current one. An example for this may be statistical models used to derive damage estimations from inundation depths for the same time step. A *past temporal dependency* exists when datasets of past time steps are required to produce a dataset for the current time step. These datasets may originate from the same model or from other models. This is, for example, the typical behavior of Cellular Automatons that can be used for flood simulations. *Cycles* in model dependency graphs require further discussion. Cycles are referred to as interdependencies between models (i.e. both models require datasets from the other model to produce datasets). For example, a groundwater model may require data from a river model and vice versa. This is unproblematic in case only past temporal dependencies exist. However, Gregersen et al. (2007) state that a situation of conflict exists when two models depend on each other while both require present or even future datasets in order to produce the current dataset. Because neither model is able to receive this data, one of them needs to extrapolate them from past ones. Such an extrapolation eliminates the cyclic dependency in the data dependency graph since it makes a dataset only depend on past datasets. Therefore, it is assumed that data dependency graphs are directed acyclic graphs (DAG).

3. Visualization requirements

The methods for the visualization of the evolution of systems mentioned in Section 1 are tailored to the representation of one system at a time. However, when dealing with integrated models, a set of potentially interdependent systems needs to be represented. For such cases, states of multiple systems, the impacts between these systems as well as selective branches need to be depicted.

3.1. Multiple states

The state of a system is made up of datasets, which are produced for a certain simulation step. Therefore, in order to give information on the whole model network for a given time step, multiple states should be represented. This can be performed by either displaying the datasets directly (e.g. if they are directly available as geospatial data) or by deriving *state indicators* for each system state (e.g., numerical values that potentially are enriched with auxiliary information such as uncertainty measures). They should reflect the system state in a way appropriate to pursue a certain visualization task. Examples to produce indicators may be counting the number of features for which a condition yields true