A flexible object-oriented software framework for developing complex multimedia simulations

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Abstract

Decision makers involved in brownfields redevelopment and long-term stewardship must consider environmental conditions, future-use potential, site ownership, area infrastructure, funding resources, cost recovery, regulations, risk and liability management, community relations, and expected return on investment in a comprehensive and integrated fashion to achieve desired results. Successful brownfields redevelopment requires the ability to assess the impacts of redevelopment options on multiple interrelated aspects of the ecosystem, both natural and societal. Computer-based tools, such as simulation models, databases, and geographical information systems (GISs) can be used to address brownfields planning and project execution. The transparent integration of these tools into a comprehensive and dynamic decision support system would greatly enhance the brownfields assessment process. Such a system needs to be able to adapt to shifting and expanding analytical requirements and contexts. The Dynamic Information Architecture System (DIAS) is a flexible, extensible, object-oriented framework for developing and maintaining complex multidisciplinary simulations of a wide variety of application domains. The modeling domain of a specific DIAS-based simulation is determined by (1) software objects that represent the real-world entities that comprise the problem space (atmosphere, watershed, human), and (2) simulation models and other data processing applications that express the dynamic behaviors of the domain entities. Models and applications used to express dynamic behaviors can be either internal or external to DIAS, including existing legacy models written in various languages (FORTRAN, C, etc.). The flexible design framework of DIAS makes the objects adjustable to the context of the problem without a great deal of recoding. The DIAS Spatial Data Set facility allows parameters to vary spatially depending on the simulation context according to any of a number of 1-D, 2-D, or 3-D topologies. DIAS is also capable of interacting with other GIS packages and can import many standard spatial data formats. DIAS simulation capabilities can also be extended by including societal process models. Models that implement societal behaviors of individuals and organizations within larger DIAS-based natural systems simulations allow for interaction and feedback among natural and societal processes. The ability to simulate the complex interplay of multimedia processes makes DIAS a promising tool for constructing applications for comprehensive community planning, including the assessment of multiple development and redevelopment scenarios.

Introduction

Brownfield lands can be characterized by the interplay of diverse natural and anthropogenic processes interacting across media and across a range of spatial and temporal scales. Effective risk management and long-term stewardship of brownfield lands typically involve gathering, integrating, and evaluating site-specific information regarding physical, chemical, and ecological processes and relationships. These data can be obtained by a variety of methods, including direct sampling and measurement of biological and environmental parameters, laboratory toxicity studies to develop dose-response relationships, extensive literature reviews, and mathematical modeling (EPA [1] and Campbell and Bartell [2]), to estimate contaminant- and species-specific doses and responses.

It is a major challenge to assemble a simulation system that can successfully capture the dynamics of complex ecological systems, such as brownfields, and an even more serious challenge to be able to adapt such a simulation to shifting and expanding analytical requirements and contexts.

Researchers have recognized the need for more integrated and comprehensive approaches to modeling and simulation that can assess several components of an ecological system simultaneously (Maxwell and Costanza [3]; Berry et al. [4]; Bennett et al. [5]; Frysinger et al. [6]; Fedra [7]; Zandbergen; [8], and Bartell et al., [9]).

Geographical information systems (GISs) have been widely used to visualize, integrate, and analyze spatial data pertinent to evaluating changes in ecological systems (for example, see Minns and Moore [10]; Akcakaya [11] (online); Band et al. [12]; DOE [13]; and Zandbergen [8]). Many of these efforts have resulted in the creation of larger, more comprehensive models that employ model-to-model or model-to-GIS linkages (Band et al. [12]; and Ortigosa et al. [14]).

The use of GIS software as an integration framework for ecological applications seems obvious because of the important role spatial dynamics has in evaluating complex ecological systems. Although these efforts have illustrated the potential of integrated modeling, they have created integration systems that are somewhat inflexible and that do not adequately reflect true interprocess dynamics. While a powerful tool for displaying and analyzing large data sets, GIS software packages do not provide an adaptive platform for integrating diverse models and simulations (Sydelko et al. [15]). For these reasons, the Dynamic Information Architecture System (DIAS) was developed. DIAS is a flexible, dynamic, and cost-effective object-oriented approach to integrating models.

Object-oriented architecture for integrated modeling

DIAS is a flexible and extensible object-oriented framework for developing integrated, multidisciplinary, dynamic simulations (Christiansen [16] and Sydelko et al. [17]). DIAS is domain-neutral, meaning that it is not designed for simulations specific to any one discipline or subject area; rather it supports the development of simulations for virtually any type of application. DIAS has been successfully utilized to build a wide range of simulations, including dynamic terrain- and weather-influenced military unit mobility assessment; integrated land management at military bases (Sydelko et al. [17,18]) a dynamic virtual oceanic environment; clinical, physiological, and logistical aspects of health care delivery; avian social behavior and population dynamics (Rewerts et al. [19]); and studies of agricultural sustainability under environmental stress in ancient Mesopotamia (Christiansen [16]).

An important design distinction of DIAS is that it is a framework – an environment and set of tools that developers utilize to build simulations. DIAS is not a model or a suite of models, but rather a flexible modeling environment within which developers build applications by either "wrapping" currently existing models and applications (including legacy models, database management systems, GISs, etc.), coding new in-line models, or building any combination of external and in-line models to create new multicomponent simulations. In this way, the DIAS framework allows new and/or existing legacy models and other applications to inter-operate in the same object environment.

The main components of a DIAS simulation are (1) software objects (Entity objects) that represent real-world entities such as atmosphere, soil, or river, and (2) simulation models (related to environmental fate and transport and ecological processes and responses) or other applications that express the dynamic behaviors of the real-world entities (such as air dispersion, stream flow, and soil microbial processes). The DIAS infrastructure makes it feasible to build, manipulate, and simulate complex ecological systems in which multiple objects interact via multiple dynamic environmental and ecological processes.

Many traditional model integration architectures create model-to-model links (Figure 1). However, as the number of models in the simulation suite grows, however, this approach becomes more cumbersome and more difficult to implement successfully. In addition, when new models are added or one model is replaced by another, the intermodel links in the system often have to undergo major revision to permit integration of the new models. To address this difficulty, DIAS extends the Object Paradigm by abstraction of the objects' dynamic behaviors, separating the "WHAT" from the "HOW." DIAS object class definitions contain an abstract description of the various aspects of the object's behavior (the WHAT), but no implementation details (the HOW); these details are addressed by other DIAS models or applications.

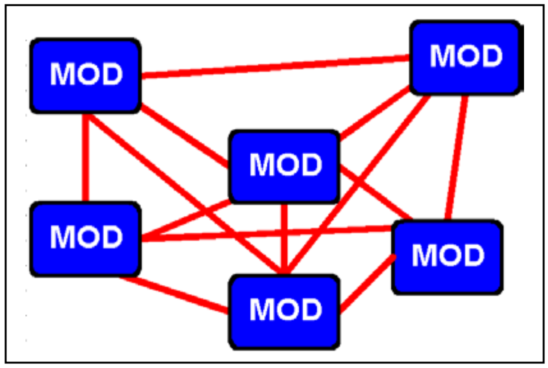

Figure 1: Traditional model-model interaction approach.

To illustrate the principle of behavior abstraction, assume a brownfields application includes a Brownfields Manager Entity object that exhibits a behavior that results in the removal of a contaminant from the soil. This behavior may be generically coded into the Brownfields Manager Entity object as “implement removal.” This generic behavior “implement removal” represents the “WHAT.” The implementation details for “HOW” the behavior “implement removal” specifically occurs would depend on the external simulation process(es) of interest. For example, depending on the objectives of the simulation, models that “implement removal” can include accelerated microbial degradation, phytoremediation, or direct soil removal.

The DIAS approach allows models to be linked to appropriate Entity objects at run time to meet the specific needs of a given simulation objective. This capability leads to even greater flexibility and extensibility of the simulation model. In DIAS, models communicate only with domain (Entity) objects, never directly with each other (Figure 2). From a software perspective, this makes it easy to add models, or swap alternative models in and out without major recoding.

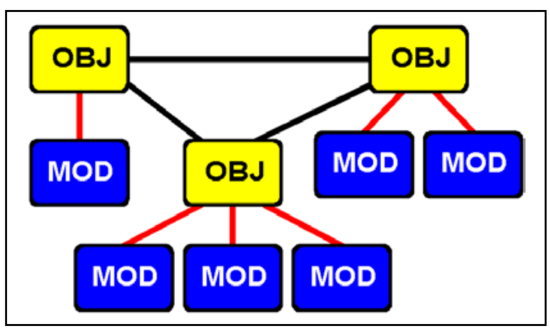

Figure 2: DIAS object-model interaction approach.

The Entity-centric design of DIAS also allows DIAS-based applications to more closely mimic the associations and relationships that exist in the real world, including dynamic feedback. In general, most models and applications have been designed to operate independently, even though effective decisions often call for assessing several components of a system simultaneously – in terms of their relationship to each other as well as how they affect broader management decisions. DIAS provides a framework for developing applications that address interprocess dynamics in a highly realistic way, in large part because the focus of the simulation is on the Entity objects and their interaction with one another. The DIAS design allows developers to articulate the dynamics of an ecosystem much more closely to the way we understand them, while at the same time not impose one-world view on the development of an application. DIAS interprocess flows are realistic because model processes affect the state of Entity objects, and thus reflect the true dynamics of the real-world system.

A schematic diagram of the DIAS architecture is shown in Figure 3. DIAS is a process-based, discrete event simulation framework. In complex DIAS simulations, both DIAS-internal and -external models and applications can interact with Entity objects to create dynamic simulations. External models or applications are made ready to participate in a simulation through a formalized process that "wraps" each model or application inside a software object for use in DIAS. This "wrapping" procedure enables the DIAS Entity objects to utilize external models to address behaviors. An important feature of DIAS is that the "wrapped" models and applications run in their native languages (e.g., FORTRAN, C, MODSIM, etc.) rather than requiring translation to a common or standard system language.

This ability to link external models and applications gives DIAS the ability to scale to increasingly complex problems. To adequately address the scientific domain of these new models, however, requires the use of domain (discipline) expertise in Entity object design. A future goal for DIAS is the development of Entity object libraries built by DIAS users for a wide variety of subject domains. The ability to reuse objects from colleagues and other researchers could speed application development. Each time a new application is developed using the DIAS framework, existing objects become more mature (new state and behavior are added) and new objects are added to the library. In this way, the library is continuously expanding, making future application development more efficient. This concept does, however, bring up the need for greater cross-discipline coordination or standardization regarding such issues as nomenclature, units, and data formats.

Entity objects are linked to the model (either internal or external to DIAS) through an object called the Process object. Process objects represent and formally define specific models that can implement specific abstract Entity object behaviors. The Process object is the only object with knowledge of both the Entity "world view" and the Model "world view." Therefore, the Process object is responsible for all data translation, unit conversions, data aggregation/disaggregation issues, etc. The Process object also controls the packaging of Entity data needed as input to models, as well as the unpackaging of model output data and its distribution to the Entities.

The data import/export utilities provide a mechanism to supply Entity objects with data for their state variables. These data-ingestion utilities have been developed to supply the object state variables from a variety of external data sources.

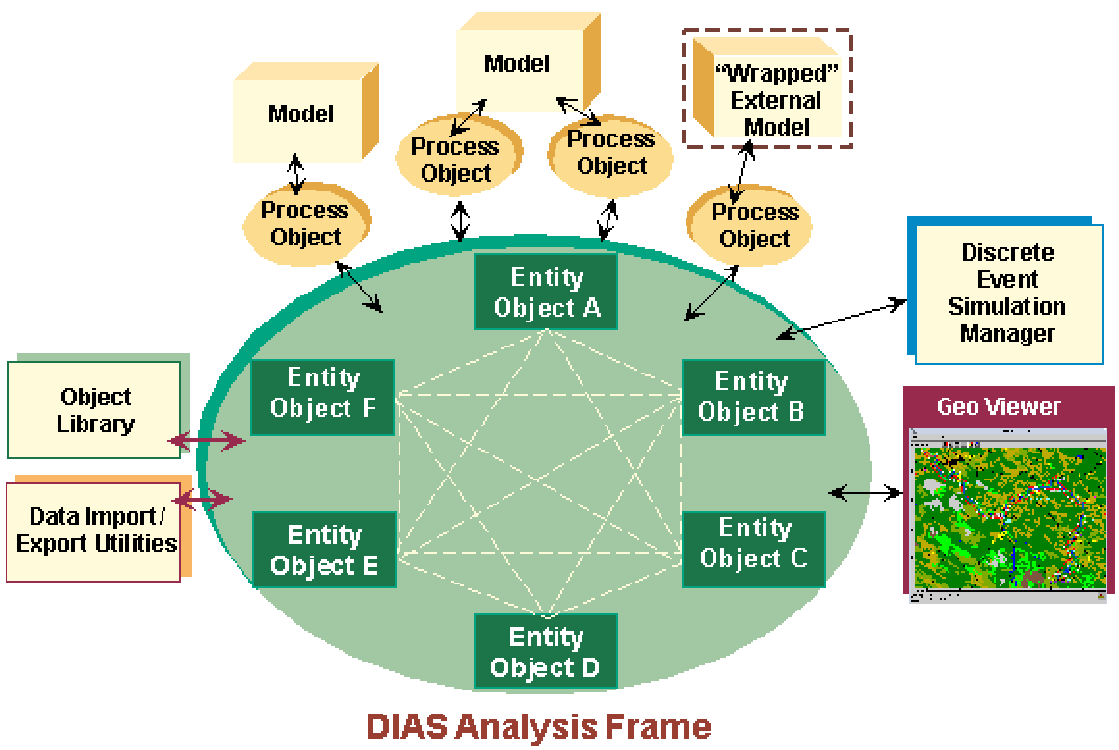

Figure 3: Schematic diagram of the DIAS architecture.

Another important feature of the DIAS framework is its ability to provide run-time feedback between models. Whereas many integration approaches require a static setup for simulation runs using a "hard-wired" sequencing of models and interactions, users of DIAS simulation applications have the freedom to choose various combinations of models and interactions for each new simulation run. Simulations are set up "on the fly," aided by an context-driven graphical user interface (GUI). The DIAS Simulation Analysis Frame establishes the connections between models and domain objects at run-time. The user need only indicate which combination of models should be included in the scenario, and this "context" drives simulation setup. An added benefit is the ability for users to track and visualize the simulation as it occurs.

The DIAS Framework includes Spatial Data Set (SDS) objects that allow Entity objects to express spatial variability in their parameters. SDSs are software objects carrying (1) a complete geometric specification for a 2-D or 3-D spatial partitioning scheme (grid, mesh, network, patchwork, etc.) that divides a region into 2-D or 3-D cells and (2) a collection of data elements for each cell. DIAS employs an object-oriented GIS module, called the GeoViewer (Figure 3), to provide real-time spatially oriented displays of an object's position and/or parameters. This GIS module is designed to navigate within a DIAS study area/frame to create, query, view, and manipulate objects. For each simulation implementation, model output parameters are generated at each time step of the simulation. In Figure 4, the GeoViewer is displaying four different aspects of a Integrated Dynamic Landscape and Analysis System (IDLAMS) simulation. IDLAMS is a DIAS application for modeling military land management and land use impacts on vegetation and wildlife habitat on army installations (Sydelko et al. [17,18]).

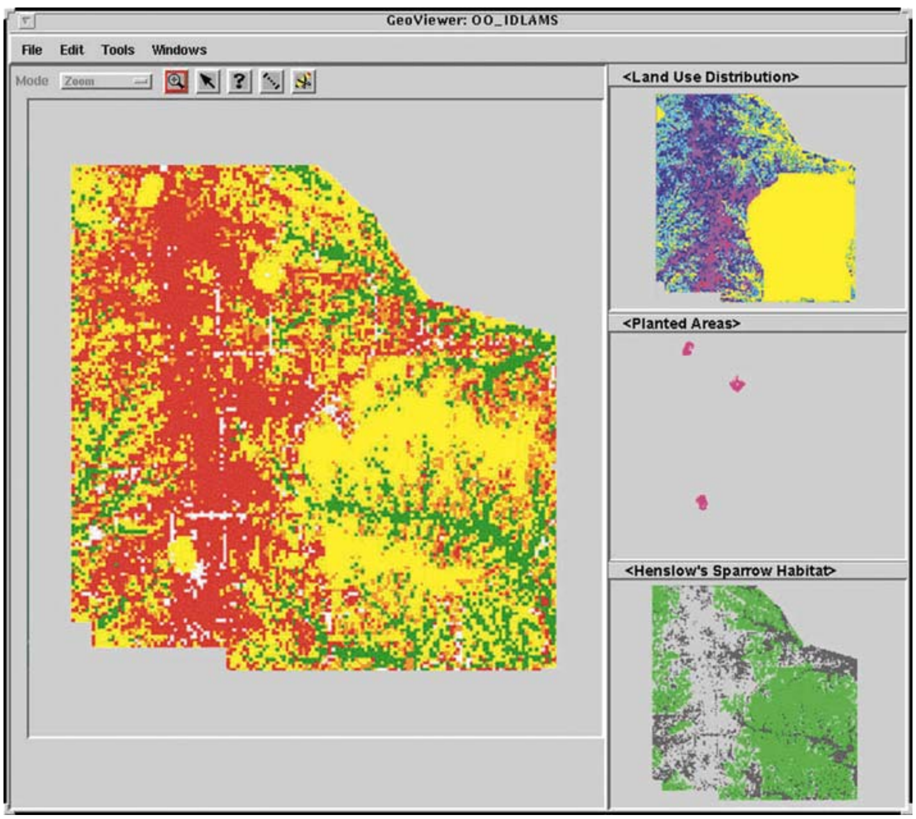

Figure 4: GeoViewer provides real-time spatially oriented displays for four different aspects of an IDLAMS simulation (vegetation, land use distribution, planted areas, and wildlife habitat).

DIAS can also link to external GISs that can perform spatial analysis and modeling functions. For instance, for the IDLAMS application, an external wildlife habitat model written as an Environmental

Systems Research Institute (ESRI®) application, was linked into the overall IDLAMS model suite. In addition, DIAS can import and export in many spatial data formats through the data ingestion utilities.

Summary and Future Direction

DIAS is a process-based, discrete event simulation framework that can be used to develop and maintain a wide variety of multidisciplinary simulations. The framework is completely object-oriented and is domain neutral, making it useful for virtually any application domain. A key benefit of the DIAS framework for development of multidisciplinary models is the ability to allow new and/or existing legacy models as well as other applications to operate in the *same* object environment. The modular design of DIAS promotes this flexibility and extensibility, which enhances cost-effectiveness and the evolution of applications.

The DIAS object-model approach to integrated dynamic simulation and modeling can assist in evaluating a diverse array of environmental problems ranging from land management to ecological risk to environmental restoration. In summary, the DIAS architecture offers enhanced capabilities to:

- Allow for the integration of existing diverse models without extensive reworking, thus capitalizing on previous investments in already available models and applications;
- Encourage the development of object libraries that contain a large number of reusable objects to represent a wide variety of natural and artificial elements of the environment, therefore reducing the long-term cost of redeveloping objects and technologies;
- Provide an integrated architecture that reflects the dynamics of living ecosystems, land uses, and land management practices;
- Support software applications that can operate at multiple spatial and temporal scales; and
- Incorporate new data, concepts, and technologies that will bring together the best available knowledge, science, and technology to address environmental problems in a scientifically defensible yet timely and cost-effective manner.

DIAS continues to be used to develop a wide variety of applications. Currently, efforts are underway to utilize DIAS for a three-compartment multimedia prototype model sponsored by the U.S. Environmental Protection Agency (EPA). In addition, there are ongoing efforts in building the Integrated Oceans application, a DIAS-based virtual maritime environment within which existing models are employed to simulate the transition of wind-generated waves in the deep water to waves in the near-shore environment, then to surf characteristics and currents. Another new application built using DIAS is CASCADE, the Complex Adaptive System Countermeasure Analysis Dynamic Environment. CASCADE is an object-oriented software system for building and running agent-based multidisciplinary simulations that concurrently address socioeconomic, psychological, environmental, etc., factors to support countermeasures analysis. The first full implementation of CASCADE is CASCADE-CD, a counter-drug simulation software system prototype to aid drug interdiction analysts in deriving and justifying force structure and operational planning recommendations for combating the South American cocaine trade.

DIAS is an integration framework capable of integrating the wide variety of models, simulation and data necessary to assess the complexities of brownfields assessment. Entity objects can be created that represent the multiple interrelated aspects of the ecosystem, both natural and societal. The Entity objects can exhibit specific behaviors, either directly coded within DIAS or provided by linked external models and applications. DIAS can address both the spatial and temporal scale issues required for complex dynamic modeling necessary in brownfields assessments.

While the generic design of DIAS makes it a robust framework for multidisciplinary modeling, this benefit necessitates a more complex development environment than that typically seen in more domain-specific simulation development software. Currently, DIAS users must have advanced object-oriented software engineering skills to readily implement applications in the framework. The DIAS Application Programming Interface (API) provides instruction and examples that help guide application developers through creation of simulations, however, there is presently no GUI to assist this process, and developers must extend the framework objects directly by adding new source code. As a first step in assisting programmers, an API has been developed to help application developers utilize the framework.

Currently, DIAS users are typically Java programmers. However, the DIAS paradigm is beginning to be adopted by other research groups who are building and enhancing the application development interfaces for specific areas. The Army Corps of Engineers Engineering Research and Development Center has acquired DIAS to build modeling and simulation applications related to military land management. The EPA is developing the Multimedia Integrated Modeling System (MIMS) framework, a software infrastructure or environment that will support constructing, composing, executing, and evaluating complex modeling studies. MIMS is being developed to support complex cross-media modeling. The MIMS framework uses DIAS for its model coupling paradigm and execution management software. The DIAS software library provides basic templates for domain objects and models and capabilities for constructing interacting sets of models and executing those models in the proper order. The MIMS project is supporting the addition of new capabilities to the DIAS framework. An interface on top of DIAS, the MIMS framework layers generic user interfaces, well-defined parameter types, functionality that minimizes the programming effort required to incorporate new models into a MIMS simulation, and additional tools to support modelers.

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