Service-oriented model-encapsulation strategy for sharing and integrating heterogeneous geo-analysis models in an open web environment

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Abstract

Earth environment is extremely complicated and constantly changing; thus, it is widely accepted that the use of a single geo-analysis model cannot accurately represent all details when solving complex geo-problems. Over several years of research, numerous geo-analysis models have been developed. However, a collaborative barrier between model providers and model users still exists. The development of cloud computing has provided a new and promising approach for sharing and integrating geo-analysis models across an open web environment. To share and integrate these heterogeneous models, encapsulation studies should be conducted that are aimed at shielding original execution differences to create services which can be reused in the web environment. Although some model service standards (such as Web Processing Service (WPS) and Geo Processing Workflow (GPW)) have been designed and developed to help researchers construct model services, various problems regarding model encapsulation remain. (1) The descriptions of geo-analysis models are complicated and typically require rich-text descriptions and case-study illustrations, which are difficult to fully represent within a single web request (such as the GetCapabilities and DescribeProcess operations in the WPS standard). (2) Although Web Service technologies can be used to publish model services, model users who want to use a geo-analysis model and copy the model service into another computer still encounter problems (e.g., they cannot access the model deployment dependencies information). This study presents a strategy for encapsulating geo-analysis models to reduce problems encountered when sharing models between model providers and model users and supports the tasks with different web service standards (e.g., the WPS standard). A description method for heterogeneous geo-analysis models is studied. Based on the model description information, the methods for encapsulating the model-execution program to model services and for describing model-service deployment information are also included in the proposed strategy. Hence, the model-description interface, model-execution interface and model-deployment interface are studied to help model providers and model users more easily share and integrate geo-analysis models in an open web environment. Finally, a prototype system is established, and the WPS standard is employed as an example to verify the capability and practicability of the model-encapsulation strategy. The results show that it is more convenient for modellers to share and integrate heterogeneous geo-analysis models in cloud computing platforms.

1. Introduction

A substantial number of extremely complicated and constantly evolving geo-phenomena and geo-processes occur in Earth’s environment (Serreze, 2011; Albanesi and Albanesi, 2014). Geo-analysis models are considered important tools for simulating...
these geo-phenomena and geo-processes (Parsons, 2011; Lin et al., 2013a, 2013b; Sudo et al., 2013). Through years of research, numerous geo-analysis models (on various geo-problems, study areas, spatiotemporal scales) have been built in a variety of disciplines (e.g., Goodchild et al., 1996; Basnyat et al., 2000; Dickinson et al., 2006; Todorova et al., 2010; Dennis et al., 2012; Li et al., 2013, 2015; Zhang et al., 2014, 2015a; Zhu et al., 2015; Yin et al., 2015). However, when simulating synthetic geo-processes and complicated geo-phenomena, the knowledge of a single discipline can hardly address all situations in the environment. The study of sharing and integrating geo-analysis models has been shown as an efficient method to connect researchers across disciplines and to further solve comprehensive geo-problems, especially in interdisciplinary research (Argent, 2004; Argent et al., 2006; Chen et al., 2011; Lin et al., 2015). Sharing and integrating geo-analysis models in an open web environment can also reduce the cost of applying geo-analysis models in practice, thus promoting modelling research (Sancho-Jiménez et al., 2008; Nativi et al., 2013).

To share and integrate heterogeneous geo-analysis models, several problems regarding the heterogeneities of various models must be considered. Because geo-analysis models are developed using different technical approaches by individual researchers or research groups, they are often built on different platforms (e.g., Windows and Linux), coded in different programming languages (e.g., FORTRAN, C/C++, Python) and designed with different user interfaces (e.g., console command line, execution file, dynamic link library). Moreover, it is generally difficult for researchers to understand models from other disciplines. To reduce the heterogeneities of geo-analysis models, encapsulation (also referred to as wrappers in the software development field) studies are necessary.

To date, several model sharing and integration methods have been studied using a variety of theoretical and technological approaches. Some methods are designed to integrate specific models: the coupling of HEC-RAR with MODFLOW to simulate stream-aquifer interactions (Rodriguez et al., 2008); SWAP and MODEFLOW-2000 for modeling groundwater dynamics (Xu et al., 2012); and land-use forecasting models and hydrologic models for improving land-use decision support (McColl and Aggett, 2007). Moreover, a range of frameworks and platforms for sharing and integrating geo-analysis models has been proposed and developed to support dynamic modelling. Examples include the Spatial Modeling Environment (SME) (Maxwell and Costanza, 1997a, 1997b), ModCom (Hillyer et al., 2003), the Open Modeling Interface (OpenMI) (Blind and Gregersen, 2005 and Moore and Tindall, 2005), the European Union’s Program for Integrated Earth System Modelling (PRISM) (Valcke et al., 2006), the Common Agricultural Policy Regional Impact modelling system (CAPRI) (Britz et al., 2010), and the Community Surface Dynamics Modeling System (CSDMS) (Peckham and Hutton, 2009). Different modelling frameworks employ various model encapsulation methods. Some frameworks use re-programming (Sucar, 2009), while others use input/output data conversion (Pullar and Springer, 2000), and some are based on command calling (Lei et al., 2011).

However, most of these integration frameworks are field specific, and few of these frameworks support the sharing and integration of models over the Internet. Trends in the Internet and in software engineering development over the past 15–20 years have promoted a range of web-based applications that allow users to more easily communicate with each other and access resources. Because geo-analysis models are typically distributed globally and are owned by researchers in multiple disciplines, sharing and integrating geo-analysis models in an open web environment can facilitate the access and use of geo-analysis models (Laniak et al., 2013; Chen et al., 2014). Through this open web environment, model providers can offer their own models, and model users can reuse and integrate these models. Service-oriented Architecture (SOA), which is widely used in the information-sharing and business-processing fields, has been used to integrate model data and geo-analysis models worldwide (Erl, 2008).

Based on the web architecture, the Open GIS Consortium (OGC) has drafted several specifications concerning data and modelling services, such as the Web Mapping Service (WMS), Web Feature Service (WFS), and Web Processing Service (WPS). Based on the WPS standard, much software has been developed to help modellers build model services, such as the PyWPS (Python Web Processing Service), 52North project and QGIS (Quantum GIS). In addition, Simple Object Access Protocol and Web Service Description Language (SOAP/WSSDL) and ‘Model Web’ have been studied in terms of the sharing and integration of geo-analysis models (Geller and Turner, 2007). Cloud computing, which is commonly viewed as an efficient method of sharing resources in an open web environment, has also been investigated for geo-analysis modelling services (Wen et al., 2013). Based on these web-based model-services, scientific workflows and business process workflows can be constructed (such as Kepler, WS-BPEL). However, the lack of user control and interactivity during execution appears to limit the application in using model-services (Granell et al., 2013; Zhang et al., 2015b).

Cloud computing can provide massive storage and computational resources for the execution of geo-analysis models. When using a cloud-computing platform, the original model resources are moved from a personal computer to transparent computation servers. Although cloud computing and other web processing architectures provide an open web environment to share resources (model services can also be treated as resources), several existing legacy models cannot be directly uploaded to a server node and used for a model service. The encapsulation work of geo-analysis models is important, and the following difficulties regarding this work are observed.

(1) Heterogeneity of geo-analysis model descriptions. In addition to the execution heterogeneities, substantial variations occur in multi-disciplinary geo-analysis models caused by the different research contexts of disciplines (modellers have difficulties in understanding and employing geo-analysis models of another discipline). A structured model-description method is required to meet the demands of model discovery by model users and model encapsulation by model providers.

(2) Differences between model execution behaviour and web services. Because geo-analysis models typically involve several computation states that partially reflect real geo-processes, model users must act according to the specific requirements in these states. However, the basic architecture of a web service is designed as a simple request–response process, which is in contrast to the execution behaviour of geo-analysis models. Therefore, the description of model execution behaviour that meets the demands of web service architecture should also be considered in model encapsulation.

(3) The deployment information of model-services must be communicated between model providers and model users. In an open web environment, geo-analysis models will be offered and deployed by model providers, and model users employ these models within the same web environment. However, model users who want to use a geo-analysis model and want to copy the model service into another computer still encounter problems (e.g., they cannot access the hardware/software dependencies information). Therefore, model encapsulation should contain sufficient information (flexible and extendable) for modellers from different countries with different research backgrounds.
This study does not focus on building a model-integration framework or model service architecture to solve all the problems in model sharing and integration; instead, we attempt to develop a strategy to encapsulate geo-analysis models that can further support the sharing and integration of models in an open web environment. As shown in Fig. 1, the encapsulation results can be published as model services after encapsulating the original codes or execution programmes. Web Service technologies (for example, the WPS standard) can be used to publish model services, and cloud computing platforms can contain these services. Furthermore, the main idea of this study is that model providers should be able to encapsulate their original geo-analysis models by implementing a set of model encapsulation interfaces. Model users can obtain sufficient information regarding encapsulated models and related resources through these interfaces. The proposed service-oriented encapsulation strategy will be used to study the description method for heterogeneous geo-analysis models. The method for encapsulating the model-execution program to model services and for describing model-service deployment information is included based on the model descriptions. Based on this encapsulation strategy for geo-analysis models in an open web environment, model providers can organise model descriptions, model-execution behaviour and model-deployment information in a structured and extendable manner. Moreover, model users can access models, prepare model input data, and use model services more easily; thus, the difficulty of sharing and integrating heterogeneous geo-analysis models in an open web environment can be reduced.

The remainder of this article is structured as follows. The basic idea behind the model encapsulation strategy is introduced in Section 2. In Section 3, the detailed model-encapsulation method with the design of the model-description interface, model-execution interface, and model-deployment interface is explained. Section 4 introduces the realisation of a prototype system and related experiments. Finally, the conclusions and a discussion of the study are presented in Section 5.

2. Basic idea of the model-encapsulation strategy

The proposed model encapsulation strategy focussed on the sharing process between model providers/users and model services. As shown in Fig. 2, model providers ought to describe the models that they want to publish; therefore, model users can more easily find and use models by searching with descriptive keywords. Regarding this process, the WPS standard includes items to support “a human readable description” (according to the Web Processing Service 2.0 Standards Working Group, http://www.opengeospatial.org/projects/groups/wps2.0SWG). However, the WPS standard only permits a relatively static description (i.e., once a model service is launched, the description information is assigned and can be difficult to modify). Geo-analysis models are developed by individual researchers and research groups from around the world. The descriptions of geo-analysis models are complicated (e.g., presented by using different languages) and typically require rich-text descriptions (e.g., videos and animation pictures) and case-study illustrations, which are difficult to represent when using a single web query service (e.g., GetCapabilities and DescribeProcess requests in the WPS standard).

In Fig. 2, model-related resources (data service, model service, and computer service) are treated as disparate web cloud nodes, and the specific storage location is typically transparent for users. Additionally, numerous web transmission methods are available to users for accessing these resources (e.g., HTTP, P2P, WebSocket). The proposed encapsulation strategy is not tightly bound to any web architecture or web transmission method; instead, it offers a simple method for users to apply model services in practice with the interface designation. The designed interfaces can provide various approaches for model providers to fully describe models, wrap model-executing programs into model services, and deploy models into specific web nodes. Additionally, through the designed interfaces, model users can obtain model descriptions, run models with full control, and integrate different models to solve geo-problems.

Geo-analysis models should be encapsulated and published according to the specific technology architecture (such as the ASP.Net platform or the JAVA platform) so that model users can correctly prepare input data and utilise models through corresponding web requests and response commands. Considering the working process of model providers and model users, the proposed encapsulation strategy consists of three basic interfaces: the model-description interface, the model-execution interface, and the model-deployment interface.

(1) The model-description interface is implemented to unambiguously and fully describe model information. Using the model-description interface, model providers can describe the models in a flexible and structured manner (with extendable language versions and foreign well-known website linkages), and model users can obtain this descriptive information. With the model-description interface, the heterogeneity of geo-analysis model descriptions can be reduced.

(2) The model-execution interface is designed to explain the models’ input and output (IO) data and execution behaviour. The model-execution interface includes the model data description method and the model execution behaviour description method and is typically combined with programming tasks. The model data description method is used to reduce the heterogeneity of the model data, and the model execution behaviour description method is used to convert complex model computation states into web services. By employing the model data description method and the model execution behaviour description method, heterogeneous models can be more easily encapsulated as model services. In addition, model users can obtain information on model execution states and take action according to the state using the model-execution interface.

(3) The model-deployment interface is used to describe model-service deployment information, such as the web resource location of the computer that contains the model service.
and the model execution dependencies. To utilise geo-analysis models as model services, model providers should offer sufficient "install" information to deploy models on computers. In addition, model users need to know the deployed location so that model services can be invoked. Using the model deployment interface, model providers can more conveniently publish geo-analysis models as services, and model users can use these model services with additional execution background information, which can facilitate model users' understanding of model services.

Through the three main encapsulation interfaces, the collaboration between model providers and model users becomes easier, thus reducing the difficulty of sharing and integrating geo-analysis models in an open web environment. Model encapsulation focuses on the working process in which model providers offer information that is sufficient for model users to understand and use the shared model resources. Model encapsulation is independent of specific technology approaches and can be used when implementing model services (for example, the WPS standard can be used to more easily implement the proposed model encapsulation interfaces by extending some request methods of the WPS standard).

3. Encapsulation strategy for heterogeneous geo-analysis models

3.1. Description interface of geo-analysis models

When solving synthetic environment problems by integrating multiple geo-analysis models, the first step is to find appropriate models according to the modelling objective. Geo-analysis models have been developed by a variety of researchers or research groups; they are often dispersed across the web environment. Therefore, model discovery is a complex issue because the volume and diversity of geo-analysis models grow exponentially. The ambiguity of search keywords leads to difficulty in finding models of interest because typical concepts in one discipline may be obscure to researchers in other disciplines. The flexibility and variety of model descriptions hinders model users from understanding models because researchers and research groups are from different countries and speak different languages. Therefore, complete and unambiguous descriptions of geo-analysis models are required.

Category services can facilitate locating resources of interest (Bergner, 2007). In addition, some model-integration frameworks have already been used to construct various types of model category systems, which are typically developed using a tree structure (Peckham and Hutton, 2009). However, building a comprehensive category system to describe all categories of models is difficult because environmental modelling research is changing, and more geo-analysis models are emerging. Regarding these problems, this study does not focus on building a new model category system; rather, we attempt to design a management solution to integrate different categories of systems.

In the software engineering field, language packages and plug-in architectures have been proposed and have been shown to be efficient methods of integrating software representation interfaces and application modules. Borrowing from these basic concepts, the proposed model-description interface (which is represented as the IAttributeSet, as shown in Fig. 3) consists of two main item collections: CategoryCollection and LocalAttributeCollection. Both of these collections are extendable: CategoryCollection is a set of the ModelCategory collection, and LocalAttributeCollection is a set of the ModelLocalAttribute collection. The model-description interface is designed as shown in Fig. 3.

ModelCategory is designed to present information on the model category to which the described model belongs. The Principle attribute of the ModelCategory object defines the unified name of a model category system, and the Path attribute provides the level location of the described model in a model category system. As shown in Fig. 4, the MODFLOW model is categorised in the Community Surface Dynamics Modeling System (CSDM) system (Principle) and belongs to the "CSDM/Terrestrial models" subcategory (Path).

ModelLocalAttribute is designed to structurally describe model declarations. LocalizationEnum describes the language, such as
In addition, behind the execution program representation, geo-analysis models are the abstractions of geographical information and geo-processes. Workflows with multiple execution steps are often used to simulate real environmental running states. The ability to understand execution step information and to perform corresponding actions based on the specific execution step is typically required by model users. Model execution behaviour information should be included within the encapsulation geo-analysis models so that the original geo-process characteristics of the models can be retained; simply regarding geo-analysis models as “give input and get output” black boxes cannot meet demands in complex modelling applications.

The descriptions of the model data and model execution behaviour are similar to those obtained from Data Provenance research. Many studies regarding Data Provenance have been conducted to track the input–output relationships and geospatial analysis history in workflow systems (Alonso and Hagen, 1997; Wang et al., 2008; Malaverreri et al., 2012; OGC, 2014). In addition, the Open Provenance Model (OPM) can handle spatial data provenance, including, in the context of Earth data processing systems (Tilmes and Fleig, 2008), geospatial web services and geoprocessing service chains (Yue et al., 2010). In this paper, the model-execution interface is designed to provide a “descriptive level” between geo-analysis models and specific technology implementations. Based on the model-execution interface, other data provenance applications can be developed to conduct specific geo-processing workflows. Furthermore, the model-execution interface can offer sufficient information regarding model data and model execution processes, which are necessary for data provenance work. The model-execution interface contains two main description methods: the model data description method and the model execution behaviour description method.

3.2. Model data description method

Because of the variety of research disciplines and modelling methods, different geo-analysis models have their own data requirements. The format and content of model data are diverse because of the variety of modelling disciplines and researcher designations (e.g., data in fixed formats and data that are described by flexible plain text). Considering that geo-analysis models should be implemented by a programming language, all model data are converted into variables of the employed programming languages. Using a series of basic variable types and the combination of these variable types, a flexible data description model (Universal Data eXchange model, UDX) is proposed to reduce the heterogeneity of the model data.

In Fig. 5, the Unified Modeling Language (UML) diagram of the UDX model is explained. Node and Kernel are two basic construction elements of the UDX model. Node controls the model data hierarchy structure, and Kernel controls the type of Node. Every Node has a unique Name and Kernel and possesses a NodeChildren that contains the number of child Nodes (0–n).

Kernels (DTKernels) can be divided into three groups based on type: DTKValue, DTKValueList, DTKContainer. An enumeration constant table (KernelType) is defined to assign a unique code to all Kernel types. Table 1 shows detailed information on these KernelTypes. Vector2d, Vector3d, and Vector4d are designed to help construct these kernels. Six types of values are employed in the UDX model to present basic data: Int, Float, String, Vector2d, Vector3d, Vector4d. The precision of the basic value type is not fixed. Although DTKFloatValue means that the value is a floating number (also called a decimal), the precision is not fixed to 32 bits or 64 bits. The precision can be assigned using other UDX Nodes (using a DTKIntValue Node to indicate the precision that the DTKFloatValue Node used), and the actual data can be correctly interpreted using a program that implements the UDX model.
Fig. 6 introduces the UDX data structure using Hydro Response Unit (HRU) data (Arnold et al., 1998) as an example. Watershed data should be appropriately prepared to use the Soil and Water Assessment Tool (SWAT) model, and HRU data are important input data when combined with watershed data. Fig. 6 includes two main parts: the bottom part presents the original watershed data, and the top part shows the corresponding description using the UDX model. As shown by the gears presented in the bottom of Fig. 6, the original watershed data consist of several parts organised in plain text (HRU data) and binary format (shapefile, sub basin data and sub basin's attribute data). Using the UDX model, the watershed data are described as a complicated DTKStructure node that is constructed using various objects, such as the Watershed_Name node (DTKStringValue, describing the name of the watershed), Watershed_Area node (DTKFloatValue, describing the total area of the watershed), Watershed_Boundary node (DTKVector2dList, describing the outline of the watershed), and SubbasinList node (DTKList, describing all sub-basins that are within the watershed). In the SubbasinList node, there is a list of Subbasin_Item nodes, and every Subbasin_Item node is developed using the same structure: Subbasin_ID (DTKIntValue, describing the ID of the sub-basin), Subbasin_Area (DTKFloatValue, describing the area of the sub-basin), Subbasin_Boundary (DTKVector2dList, describing the outline of the sub-basin), Subbasin_Attribute (DTKTable, describing all the attributes of the sub-basin). In the Subbasin_Attribute node, all child nodes should be of the type DTKValueList. For example, the HRU_SlopeLength node is of the type DTKFloatList, and it describes all HRU slope length values. Using this “construction” method, complicated model data can be fully and flexibly described.

In contrast to other intermediate data formats in data conversion fields, the UDX model is not only a data format but also a set of methods used to uniformly and completely describe model data. Because it is derived from the UDX model, there are two main implementations: UDX Data and UDX Schema. UDX Data is designed to interchange model data in their original format with
the UDX model. UDX Schema is designed to provide the skeleton frame information on the model data, which should remain highly consistent with the corresponding UDX Data.

Using UDX Data, the encapsulated geo-analysis models would require data in the same organisation. In addition to preparing model input data in a variety of organisations or formats, model users can utilise model data with a common method. Moreover, the integration of different models can enable the more direct interchange of input/output data.

Independent of any specific model data, UDX Schema focuses on the full and unambiguous description of model data, which can reduce confusion and difficulty in terms of data preparation. To help model providers describe model data in a more structured manner and to help model users better understand the model (so that model data can be more easily prepared), four library attachments are constructed, as shown in Fig. 7: the unit and dimension library, the semantic (or concept) library, and the spatial reference library, the data-description template library.

In Fig. 7(a), the flow velocity data from a monitor section series in a specific area of a river are described using a value table. For example, although “5” is a simple numerical value, it contains much more information, including that the speed units are presented in m/s and that the concept of these data is flow velocity. Therefore, the unit and dimension library provides a full measurement scale for the UDX data, the semantic (or concept) library provides accurate semantic (conceptual or ontological) information on the UDX data by borrowing the semantic systems and web from other disciplines, the spatial reference library provides coordinates or projection information for the UDX data (if the data are spatial), and the data-description template library provides an interface for interchanging with other domain-related or commonly used data formats (e.g., Shapefile, Geotiff, and WKT).

In Fig. 7(b), the example implementation of the UDX Schema for the flow velocity data of a monitor section series is presented. The river_edge Node is used to describe the spatial position of the river’s edge, and the general data type of this Node is Shapefile, which is represented by the ShapefileData item in the data-description template library. The unit, concept and spatial reference information are contained in the UDX Schema by linking the corresponding resource items in the unit and dimension library, the semantic (or concept) library, and the spatial reference library.

The UDX model allows users to define, understand, and prepare model data for model execution, hence reducing the difficulty in data processing when encapsulating geo-analysis models.

### 3.2.2. Model execution behaviour description method

According to the above analysis, geo-analysis models often involve a substantial amount of discipline-specific knowledge and a variety of interactions with users. Amongst all the difficulties of sharing and integrating heterogeneous geo-analysis models, the complexity of model execution behaviour plays a significant role. The execution of geo-analysis models typically involves numerous intermediate “computation steps”, which provide intermediate computation results or require model users to offer input data to continue the execution process (as shown in the left portion of Fig. 8). The model execution behaviour includes several mid-processes, and the execution flow can be invoked by other computation processes). Similarly, in the IT domain, workflows have been shown to be an efficient method of simplifying complicated data processing and information transmission work (Deelman et al., 2009). Hence, this study proposes a model behaviour description method: the State Machine-Event Response model (SM-ER model). In the SM-ER model, geo-analysis model execution processes are abstracted as states, and input/output data handling messages are abstracted as events. The interaction between the model execution and model users was described as request and response.

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**Table 1**

<table>
<thead>
<tr>
<th>Group</th>
<th>Kernel type</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTKValue</td>
<td>The kernel should be limited to DTKIntValue, DTKFloatValue, DTKStringValue, or Vector type (DTKVector2dValue, DTKVector3dValue, DTKVector4dValue). In addition, the node cannot have any child nodes; the value that the node contains must be consistent with the kernel type</td>
</tr>
<tr>
<td>DTKValueList</td>
<td>The Node has a list of values, and the values must be the same type as one of the kernel types in the DTKValue group, e.g., DTKIntList, DTKFloatList, DTKStringValueList, DTKVector2dList, DTKVector3dList, DTKVector4dList). Additionally, DTKValueList cannot have any child nodes</td>
</tr>
<tr>
<td>DTKContainer</td>
<td>Four types: (1) Structure, (2) List, (3) Key-Value, or (4) Table. The DTKContainer node itself does not hold any data. The specified kernel type also applies to the child nodes, and all the data should be stored in the child nodes</td>
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</table>


The SM-ER model is illustrated in Fig. 8. The ModelBehavior object includes ModelState sets and ModelTransition sets. The ModelTransition set describes the source state (previous execution step), the target state (the next execution step) and the condition (which indicates whether the execution can be continued) of the ModelTransition. The ModelState set consists of a name and the associated ModelEvents, which will be used to indicate data handling messages during model execution. The ModelEvent includes a name and the numbers of RequestData (designed to describe external requests for data as an external input) and ResponseData (used to describe the data submitted to the outside as an output). If a ModelEvent contains RequestData, then the model is requesting user input (transmitted by dataCallBack in UDX Data). In addition, if ResponseData is contained in the ModelEvent, then the model is providing data as an output (transmitted by data in UDX Data).

Combined with the UDX model, the execution order and data requirements of geo-analysis models can be represented by the SM-ER model. In addition, the SM-ER model can clearly reflect the execution process and can benefit from collaborative interactions between the models and the external environment. Based on the UDX model and the SM-ER model, the model execution interface is designed as shown in Fig. 9. The execution of the geo-analysis model is described by IExecutionBehavior, which includes DataDeclarationCollection (all related model data descriptions from the UDX Schema) and ModelExecutionStates (describing the execution behaviour of models). Through the IExecutionBehavior interface, geo-analysis models can be encapsulated as the interactive “state machine” so that model users can obtain the corresponding model data information (with the UDX Schema) in preparation to use the models and take appropriate actions based on the execution states that are provided by the SM-ER model.

As shown in Fig. 9, the following three basic model execution styles, which are derived from the SM-ER model, are designed to help model practitioners more easily perform model encapsulation: state simulation style, simple calculation style, and time series style.

(1) State simulation style: Geo-analysis models in the state simulation style are encapsulated as execution processes with multiple states, which conform to the SM-ER model. The state simulation style can provide a flexible approach for describing geo-analysis models. The encapsulated models of this style should implement the IExecutionBehavior interface, and the state concept in the SM-ER model is implemented as node. In addition, the state simulation style model should be constructed using one start-node, one end-node, and a range of state-nodes (0–n). Every node can be invoked using the service-calling method (request/response command) in the general web service environment; therefore, the encapsulated model can be executed through a series of web-service calling commands.
(2) Simple calculation style: Although geo-analysis models can represent complex geo-processes, most existing geo-analysis models are implemented as simple mathematical algorithms. The simple calculation style is designed to more easily encapsulate these relatively simple models. The simple calculation style is a special SM-ER model and contains only one state-node with one RequestData event and one ResponseData event. The execution of the encapsulated
models in this style is similar to the common web service use method, which involves requesting a service with some parameters and obtaining the response of the execution results.

(3) Time series style: A large number of geo-processes are time dependent and are governed by timelines during the execution of geo-analysis models. The time series style is designed to more easily encapsulate these geo-analysis models. This style is also a special SM-ER model and contains one start-node but no end-node. The simulation cycle is controlled by the start-node; once all state-nodes have been executed, a new cycle of simulation continues if model users provide a ResponseData value of YES through the web service.

Regarding the implementation of the model execution interface for encapsulating geo-analysis models, two frequently used and efficient technical methods can be employed: (a) Reprogramming and recompiling the original execution programs. By implementing the UDX model and the SM-ER model, the source codes of the original execution programs of geo-analysis models can be modified and recompiled according to the model-execution interface. (b) Wrapping original execution programs by monitoring the IO operation. For models with no source code, every read/write file operation during the model execution can be monitored using the Hook technology (Wang et al., 2009). The plug-in used for translating original data to the UDX model can be added to original model-execution programs, subsequently forming a new geo-analysis model with a model-execution interface. Both of these methods require effort by programmers. The first method demands a substantial amount of programming; however, this method allows programmers to optimise the data requirements. The second technical method involves less programming but limits the ability to improve the data requirements.

Using the model-execution interface, the heterogeneity of the model data and model-execution behaviour can be reduced, and the encapsulated models can be more conveniently mapped into a web service.

3.3. Deployment interface of geo-analysis models

Model execution often involves a massive amount of geographical data processing, the solving of complex equations, and the running of long-sequence simulations, all of which require a large amount of computing resources (NRC, 2010). With the development of Internet-based technologies, especially cloud computing architecture, geo-analysis model services are frequently deployed on distributed computer nodes to fully exploit the computing resources. In addition, the realisation of geo-analysis models depends on diverse hardware architectures, software platforms and programming languages; therefore, heterogeneity occurs at the software level. This deployment is typically very complicated.
and it often requires highly skilled engineers in computer science and web technology.

Generally, in the IT domain, running platform-dependent (e.g., Windows, Linux, UNIX, OSX) and execution-related resources (e.g., configure files, dependent dynamic link libraries) are key elements in distributing software. Moreover, because the software development cycle of geo-analysis models changes over time, several versions of geo-analysis models are developed at various times. Hence, version control is very important for the application of geo-analysis models. Based on all of these characteristics of geo-analysis models, this study designs a flexible and controllable model-deployment interface.

In Fig. 10, the model-deployment interface (IModelDeployment) is introduced. IModelDeployment consists of the Entrance attribute (of the type ModelEntrance), the ConfigureCollection attribute (a set of ModelConfigures), and the AssemblyCollection attribute (a set of ModelAssemblies). In ModelEntrance, Name indicates the execution program file name; Version provides the version flag and its related web resource link; Platform explains the platform dependencies, which are listed in the (extendable) PlatformEnum; BaseDirectory provides file system information on the execution file; and ExecutionEntrance describes the function name used to invoke the model execution programs. In ModelConfigure, key indicates the model resource type name, and value provides the file path information of corresponding resources, such as the software environment (e.g., database software dependencies and system runtime packages), execution-related files (e.g., preloaded configuration files and system demo files), model deployment help files or website URLs. In ModelAssembly, path indicates the directory of a model-execution-related assembly file, and name describes the full name with the extension of this assembly file (e.g., extension of .dll in the WINDOWS environment and .so in LINUX).

Using the model deployment interface, model providers can more clearly describe information on the model deployment in a structured manner. Model providers and model service managers can more conveniently prepare model-deployment-related resources and “install” model services on a computation node with the aid of model-deployment interfaces. Thus, the barrier to collaboration between model providers and model users can be reduced.

4. Experiment

To demonstrate the capabilities and practicability of the proposed geo-analysis model encapsulation strategy, this study implements the designed model-encapsulation interfaces within the .NET platform and establishes the experimental open web environment under the ASP.NET architecture. Fig. 11 presents the basic process of model sharing and integration using the service-oriented model-encapsulation strategy.

The model providers use four processes: (1) Define the Model. Geo-analysis models are “defined” using the Model Description Interface (which contains the model category system and localisation information). (2) Encapsulate the Model. The original model computation logic is abstracted as the “model core”, and the geo-analysis models’ programs are encapsulated using the SM-ER model and the UDX model (implementing the Model Execution Interface). (3) Deploy the Model. The Model-Deployment Interface is implemented to help model providers collect and organise all the dependencies of a geo-analysis model.

Through this three-step process, model providers can offer their model resources (represented as the Model Description Documents) to the model-sharing web environment. As shown in the lower right portion of Fig. 11, the Model Description Document is designed to implement model encapsulation results in an integrated manner. The Model Description Document uses XML to organise information regarding the geo-analysis model. The root node is ModelClass (a well-known name and a global unique ID) and contains the three following main child nodes: (1) the Attributes node, a serialisation of the model-description interface, which consists of the Categories node (indicates the model category information) and the Localizations node (which stores the language-related description information); (2) the Behaviour node, a serialisation of the model-execution interface, which consists of the DatasetDeclaration node (describes model data) and the StateGroup node (describes model execution steps); and (3) the Runtime node, a serialisation of the model-deployment interface, which consists of the Configures node (the model’s runtime resources) and the Assemblies node (execution-dependant assemblies).

After submitting the model to the shared web environment via the Portal Website, (1) the model is deployed to the Computation Platform (the Deployment Workspace interprets the deployment information from the Model Description Document), and (2) a corresponding model service item is registered to the Model Resource Library (which can be queried from the Portal Website).

Therefore, from the perspective of model users, (1) the interested geo-analysis model service information can be discovered through the Portal Website, (2) the information for the preparation of running the model of interest can be accessed using the Model Execution Interface, and (3) model users can call and then run model services that are contained in the computation platform via the retransmission of the Portal Website.

Using an example of a typical geo-analysis model’s encapsulation process, the proposed model-encapsulation strategy is...
Fig. 11. The basic process of encapsulating geo-analysis models.

Fig. 12. Encapsulation example of the DInfFlowDirection model in TauDEM.
presented in Fig. 12. In this figure, one of the TauDEM models (Terrain Analysis Using Digital Elevation Models, http://hydrology.usu.edu/taudem/taudem5/index.html) is employed to demonstrate the encapsulation process. The top-left portion of Fig. 12 shows the original execution program (Dinfflowdir.exe) as well as its related dependencies (e.g., mpich2.dll and mpich2mppe.dll) and runtime resources (the Visual C++ runtime library, vcredist_x86.exe). A set of software development kits (SDKs) was developed to help modellers implement the SM-ER model to encapsulate their original model resource and to link the execution behaviour with web service calling commands. The basic programming code of the model encapsulation is shown in the top-right of Fig. 12 (using C# style programming code to expound the encapsulation method). The execution of the model should be grouped into execution states (OnEnterState/OnLeaveState functioning in the mContext is the ModelExecutionContext). The implementation of ModelExecutionContext is dependent on the specific web service architecture. In this study, ASP.Net is employed to contain the ModelExecutionContext. For the execution process of the execution state, a RequestData Event is invoked to obtain input data. After the execution of the specific model, a ResponseData Event is invoked to return the computed result. After encapsulation, the execution process can be considered as entering the SystemStart state, entering the Run state, invoking a RequestData event, executing the computation with input data, returning the result of a responseData event, and exiting the Run State or exiting the SystemStart state.

The model description document is constructed using XML, as shown at the bottom of Fig. 12. The name of this model is “DInFsFlowDirection”, and a GUID is assigned to represent the unique model. (1) The model-description interface is implemented as the AttributeSet node, with category description of “CSDM System” and “CSDM/Terrestrial/TauDEM” and localisation attributes in Chinese and English. (2) The model-execution interface is implemented as the Behaviour node, and the DataDeclarations node contains the UDX Schemas that indicate how to prepare the input data (as GeneralData.ShapefileData for this model) and define the output data (as GeneralData.GeoTiffData for this model). In addition, a “RUNSTATE” node that contains one load data event and one return data event is used to wrap the original execution process. (3) The model-deployment interface is implemented as the Runtime node, with a version number of “5.0”, a platform dependency of “Windows_X86”, and other deployment-related resources that are given in the Configures and Assemblies nodes.

In Fig. 13, the GUI tool used to implement the geo-analysis model-encapsulation process is presented. The model description panel is developed to help model providers describe model category system information and model localisation information. The model behaviour definition panel is developed to help model providers describe the execution states of the model. The definition of these model execution states should track the real execution process of the corresponding encapsulated model program. Finally, the model data definition panel is developed to help model providers define and convert original model data used within the model execution states.

Based on the implementation results shown in Figs. 11–13, a variety of Web Service technologies can be employed to publish model services. This study uses the WPS standard as an example to transmit data between clients and servers. As shown in Fig. 14, the DescribeProcess request contains information regarding the model declaration document information that can be obtained using an external link, and model users can access this information by visiting a new URL. Similarly, the DataInputs and ProcessOutputs nodes describe the model data using external links that contain the...
UDX Schema. In this manner, the original organisation of the WPS standards is the same, and information regarding the model service is extended. Regarding the **Execution** operation, the input UDX data should be uploaded to the data server, and the original XML file (posted to the WPS server) uses the URL of the UDX data as Input-Data. This study developed a WPS server program to interpret web requests and conduct model execution. The computation results are provided to the user clients as downloadable files, and the URLs are contained in the WPS XML output document.

According to the above analysis, the project group designed and developed a prototype system of sharing, integrating and executing geo-analysis models in an open web environment. Fig. 15 shows some of the geo-analysis models in the model library built by encapsulating typical models from several disciplines. In Fig. 14, using the WPS standard to publish a model service.

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addition, geo-analysis models from several disciplines were encapsulated and deployed in an array of computing servers, and a portal website was constructed to manage all the model services. Model users can call these model services by performing a request using the model GUID and model service URL.

5. Conclusions and future research

The purpose of this study was to simplify model encapsulation, which is important in the reuse, sharing and integration of geo-analysis models. Using the proposed model-encapsulation strategy, heterogeneous geo-analysis models can be described in a common manner. With the proposed model-description interface, model-execution interface, and model-deployment interface, geo-analysis models and model-related resources can be described, executed and deployed more clearly, thus making it more convenient for modellers to reuse, share and integrate heterogeneous geo-analysis models.

However, geo-modelling and geo-model integration research is ongoing, and the following research topics should be addressed in the future:

(1) A more complete and automated strategy to deploy model resources. The technology and architecture of geo-analysis models vary between different model developers. The proposed model-encapsulation strategy can provide a clearer and more structured method to encapsulate these heterogeneous models; however, the deployment of model resources still requires a substantial amount of manual effort. By interpreting the deployment information, an automated or semi-automated method of deploying model services is required to satisfy the demands of building an extendable model library in a web environment.

(2) Designing the UDX data operation method and building the data processing library based on the UDX model. After the encapsulation of geo-analysis models, input and output data of the model execution can be formed in a common manner. However, model data pre-processing is still necessary and essential for using and integrating geo-analysis models, especially for interdisciplinary modelling, and it often demands a substantial amount of programming efforts. Building an extensive model data-processing library can reduce the effort required of model users. Moreover, UDX schemas require further research and development, whereby an effective mapping library of existing data formats to UDX schemas should be established so that model practitioners can more efficiently encapsulate existing geo-analysis models.

(3) A set of utilities must be developed to help modellers more easily encapsulate geo-analysis models. Using the IO hook technology, model-encapsulation methods can be more efficiently programmed and recompiled. In addition, a programming template should be designed and developed to help modellers more effectively write the encapsulation program code.

(4) More completed applications that use different web transmission methods (HTTP, P2P and WebSocket) to construct modelling environments or geo-processing systems should be designed and developed. When implementing model services using the WPS standard, it is simple to verify the capabilities of the model-encapsulation strategy. In addition, the WPS standard can be extended to support more comprehensive descriptions of geo-analysis models. Based on cloud computing, the encapsulated results of geo-analysis models can be deployed using different computation servers, and the web transmission method is related to specific cloud computing platforms.

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