Integrating Distributed Computational Models as Dynamic Expressions of Knowledge: The Case for Evaluating Measures for Urban Ecosystem Sustainability

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Abstract. In order to conduct simulation studies of highly complex problems, such as integrated environmental assessment of technologies, policies and other measures for making urban ecosystems more sustainable, integration of knowledge in a dynamic form from a wide range of knowledge domains is essential. We have proposed that computational models are appropriate representations of expert knowledge for such integration. Building on previously introduced concepts and software prototypes, we have been designing a dynamic computational modeling platform for studying the integrated effects of supply side and demand side technologies and policies to reduce environmental impacts and consumption of resources caused by activities in urban ecosystems such as Tokyo, Japan. This platform has been used to evaluate scenarios that include the introduction of roof-top photovoltaics, a solid oxide fuel cell combined with a gas turbine topping cycle (SOFC/GT), energy conservation measures in the residential and commercial building sectors, and waste processing and recycling systems. Here we describe the software engineering issues associated with the construction of this model integration platform and provide examples of the techniques we have developed to address those issues.

1 Introduction

Recently, in response to growing realization of the profound effect that urban activities are having on global sustainability, there is an urgent need for tools and methods to comprehensively evaluate the potential effects of technologies and policies on increasing the sustainability of a particular urban ecosystem [1]. Such comprehensive evaluation of technologies and policies in actual real-world urban systems must include a wide range of expertise from different domains of knowledge ranging from economics, to policy science, to engineering, to life cycle analysis [2]. If we are to rely on information and communication technologies (ICTs) to assist us in integrating this knowledge, the knowledge must be expressed in a form that can be examined and manipulated by a computer.

The question "what is knowledge" has an entire field of knowledge devoted to it, to which we could hardly give justice here. However, at least for expert knowledge in

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natural sciences, the old saw “data is points, information is a line through the points, knowledge is knowing what the line means and wisdom is knowing what the line does not mean” is remarkably insightful. Human expert knowledge is often described as existing in the form of mental models, which are dynamic, generalized approximations of the real world phenomenon that is “known”. In particular, these mental models enable people to consider the meaning of that phenomenon, e.g. by making inferences in relation to other things that are known.

Although printed documents have been traditionally used to express and communicate knowledge generated through scientific research, we have suggested that a more appropriate format for representing scientific knowledge might be “computational models”, which we consider to include all forms of interactive software representations of knowledge [2]. For example, computer simulations and other computational models are important media for expressing specific expertise or knowledge about the dynamics of particular phenomena in urban ecosystems [3], [4]. In order to integrate the expertise expressed in different models and to generally increase their reusability, some way of modularizing and interfacing those models is needed that preserves the dynamics and generality of that knowledge. New tools and methods have emerged in disciplines such as software engineering that could help use these computational models to integrate expert knowledge for studying complex entities such as urban ecosystems [5], [6], [7], [8]. Here, we present work aimed at applying some of these technologies to develop a distributed web-based model integration environment for enabling multiple stakeholders to work together in designing and evaluating combinations of measures for increasing sustainability in urban ecosystems.

In previous publications, we have described the development and application of a “virtual urban ecosystem” in the form of a computational model integration environment on the web [6], [9], [10]. The virtual urban ecosystem simulation platform uses the DOME (distributed object-based modeling environment) software to make available a set of computational models that give the boundary conditions of the urban ecosystem, such as census databases, input-output tables, electric power dispatch models, transportation models, and atmospheric circulation models. Another set of interfaces in the urban ecosystem simulation platform link to a variety of models of technologies and policies that have been designed to make the urban ecosystem more sustainable, e.g. by reducing environmental impacts or consumption of non-renewable natural resources. By combining the boundary-condition models with the technology and policy models, we can more comprehensively assess how the introduction of new technologies and policies might impact on environment, economy and society. We have described applications of the platform to the evaluation of specific technologies in Tokyo and other parts of Japan, from introduction of roof-top mounted photovoltaics to comprehensive plastic separation, collection and reuse system [9], [10], [11], [12], [13], [14]. In this paper, we focus on issues related to construction of the platform from a software engineering perspective, and we present some of the techniques we have used to address those issues.

In the next section, we describe the DOME software that we use as the middleware for constructing the virtual urban ecosystem platform, and we give examples of two of the modularized computational models that we have integrated by using DOME. In section 3, we describe our work to improve accessibility of the simulation platform by embedding it in a web-based collaboration platform. We end by discussing some ongoing problems related to model interfacing.

2 Supporting Integration of Dynamic Knowledge using DOME

The approach that we have taken for integrating dynamic expressions of expert knowledge related to different aspects of urban ecosystems is based on the DOME software being developed at the CAD laboratory in the Massachusetts Institute of Technology [8]. The DOME software offers tools that provide a complete environment to develop, interface, integrate and evaluate sets of computational models over the World Wide Web. DOME tools allow modelers to build, deploy, browse and integrate model interfaces to different computational models, which have been constructed using different software applications such as MS Excel and Matlab. The interfaces can be parametrically interlinked to form DOME integrated model projects. Specifically, the build tools enable the model developer to create web-accessible objects (e.g. scalar and matrix objects that have a wide range of attributes for physical units, annotation, ownership, etc.) that are mapped to the input and output parameters of the model. The build tool also provides mechanisms for creating simple computational relationships or "bridge models" between the numerical objects. In fact, the DOME relationship building environment contains sufficient numerical operators, such as a full range of matrix operators, to construct complete models of technologies to be linked into a DOME integrated model project.

In previous work, we have designed a DOME integrated model project as a comprehensive simulation platform for evaluating the overall effects of introducing a particular combination of technologies and policies to a target urban ecosystem [9]. Here, we describe two examples of computational models that have been interfaced and deployed to the model project. The first is an optimization model for central power grid planning and dispatch, and the second is a building energy consumption model that includes roof-top installed photovoltaic solar cells.

2.1 An Example of a Modularized Computational Model for Describing the Urban Ecosystem: The "Power Planning and Dispatch Model"

The "Power Planning and Dispatch Model" has been described in detail in [10]. The DOME input objects include a matrix object that contains the representative power demand curves (e.g. summer weekday, summer weekend, winter weekday, winter weekend, mid-season weekday, mid-season weekend, and peak power demand day) in the targeted urban ecosystem, and a set of vector objects containing the installation costs, running costs, conversion efficiencies, capacity limits, and load following constraints for each of the power generation types available in the region (Fig. 1). The output objects are a matrix object giving the hourly dispatch to each power generation type for the representative power demand curves, and scalar objects giving the total CO_2 emissions and total cost.

In the instance of the “Power Planning and Dispatch Model” used in [10], the power generation types consisted of hydropower, nuclear power plants, LNG fired power plants, coal fired power plants, oil fired power plants, gas combined cycle power plants, energy recovery using pumped water storage, and a novel technology that combines a solid oxide fuel cell, which uses natural gas, with a natural gas turbine topping cycle (SOFC/GT) [11]. The basic DOME interface for the power planning and dispatch model showing the input and output parameter objects is shown in Fig. 1. A custom graphic user interface that we developed for the model is shown in Fig. 2.

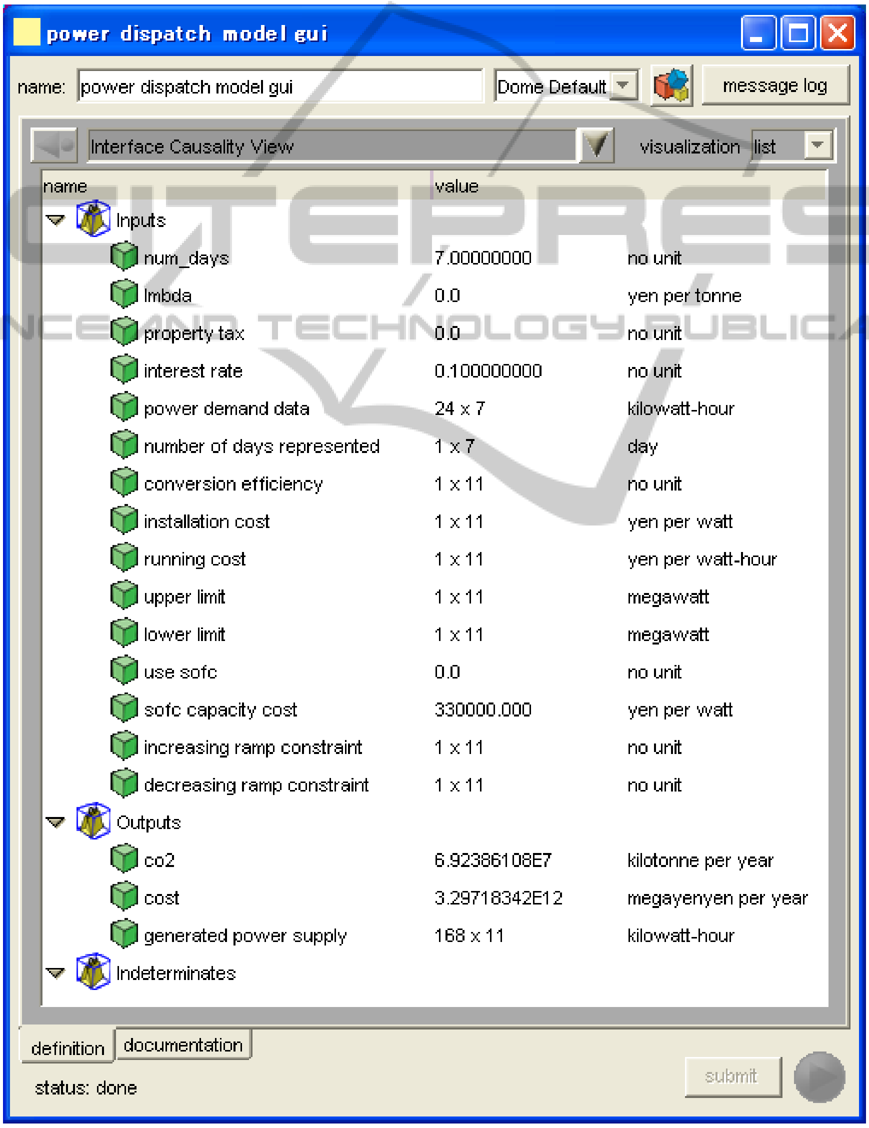


Fig. 1. The default DOME interface for the “Power Planning and Dispatch Model”.

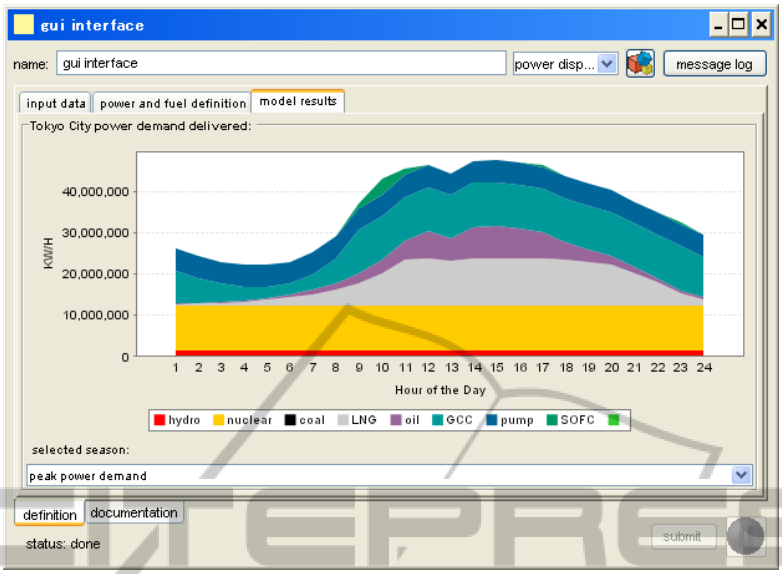


Fig. 2. The custom graphic user interface for the "Power Planning and Dispatch Model".

2.2 An Example of a Modularized Computational Model for Describing a Technology: The "Residential Building Energy Conservation Model"

In order to evaluate the potential for reducing electricity consumption in the residential sector, we have used DOME to modularize the computational model for residential buildings shown in Fig. 3 [15]. The model, which is implemented in MS Excel with VBA, uses inputs in the form of a set of demand-side countermeasures selected by the user and a specified region of Japan. It then outputs the consumption of electricity, natural gas and other energy sources by all of the residential buildings in that region from the year 2000 to the year 2050 averaged over five year time periods. The demand-side countermeasures include both standard energy conservation measures such as window insulation and efficient electric appliances, which are represented as DOME Boolean objects, and demand-side power generation using roof-top mounted photovoltaic (PV) cells, which is represented as a DOME vector object giving how much area of PV cells will be introduced each year. Outputs are represented as DOME vector objects giving the demand at each time period for each energy type.

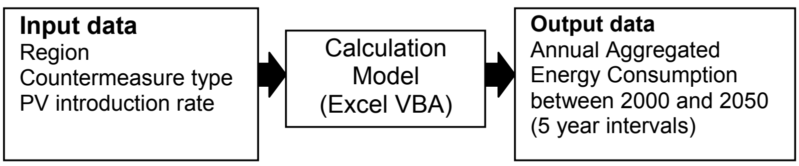


Fig. 3. Outline of the "Residential Building Energy Consumption Model".

3 A Web-based Dynamic Knowledge Integration Platform

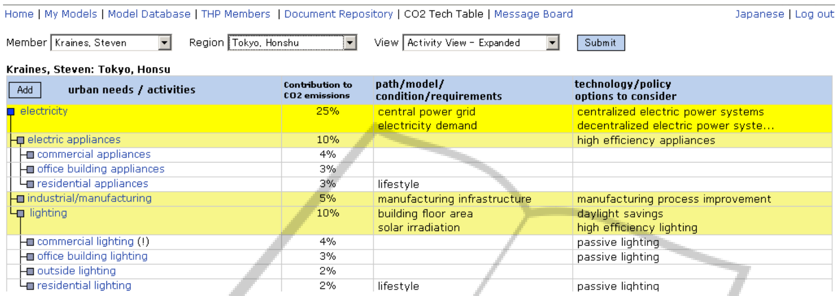
We have been developing a Web-based collaboration platform to support communication of knowledge between different experts towards the goal of evaluating technologies and policies for mid to long term mitigation of CO_2 emissions in urban regions in order to achieve Low Carbon Societies (LCSs) [16]. The platform is intended to form a structured basis for supporting smooth and seamless exchange of knowledge from multiple disciplines, knowledge that is related to various measures for achieving LCSs. A central component of this platform is a dynamic web interface called the "CO_2 Tech Table". The CO_2 Tech Table enables experts to interactively manipulate knowledge regarding the characteristics of CO_2 mitigation options in the context of specific CO_2 intensive urban activities; therefore, we can consider it to be a form of computational model of that knowledge.

The CO_2 Tech Table has three parts, which are indexed to specific urban ecosystems being studied. On the left, an expandable tree of the major CO_2 emitting activities allows users to estimate the contribution of each activity to the total CO_2 emissions. In the center, the user lists models and data resources for evaluating countermeasures for CO_2 emissions from a specific urban activity. On the right, the user enters the technologies and policies for CO_2 mitigation being studied, together with expected reduction of CO_2 emissions and time scales, etc. The semantics for each of the parts of the CO_2 Tech Table are grounded in a formalized ontology that we have developed to express knowledge in the domain of sustainability science [17].

The CO_2 Tech Table also includes a database of regional information for urban ecosystems that are being studied. In the particular application we have implemented for the study of LCSs in Japan, the target cities are Tokyo, Sapporo, Naha, Kagoshima, and Utsunomiya. These cities were judged to be representative of the variation in size, climate conditions, and lifestyles of cities in Japan. Each user is provided with a set of columns for each urban region or city that is targeted. In addition, the CO_2 Tech Table supports multiple user accounts, and it manages the personal information of each user (such as contact information and publication lists) together with the tables for classifying and organizing knowledge related to mitigation of CO_2 from urban activities.

A view of the CO_2 Tech Table that is filled out with information for the target city Tokyo is shown in Fig. 4. The user, Steven Kraines, has entered several urban activities, classified into general categories, which are logically defined within the ontology framework. For example, various activities related to electricity consumption by appliance use and manufacturing processes are grouped under the category "electricity". In the center, the user has indicated that a dataset called "central power grid electricity demand" is necessary for investigating the CO_2 mitigation potential associated with electricity consumption in urban regions. In addition, for each of the different types of electricity consumption, the need for data such as lifestyle parameters and building floor area is indicated. Finally, in the right column, the user has listed the technologies and policy options he believes to be effective for realizing CO_2 mitigation in the context of each of the types of activities given in the left column.

The collaboration platform also lets members publish a variety of knowledge resources to the web, including computational models. We have used the DOME software to create simple web page interfaces that let users dynamically operate the computational models that have been published to the web platform through DOME. By connecting the model interfaces to the model requirement specifications in the CO_2 Tech Table, we can relate the interfaced models to the ontology-based knowledge classification that is expressed there.



Home | My Models | Model Database | THP Members | Document Repository | CO2 Tech Table | Message Board | Japanese | Log out

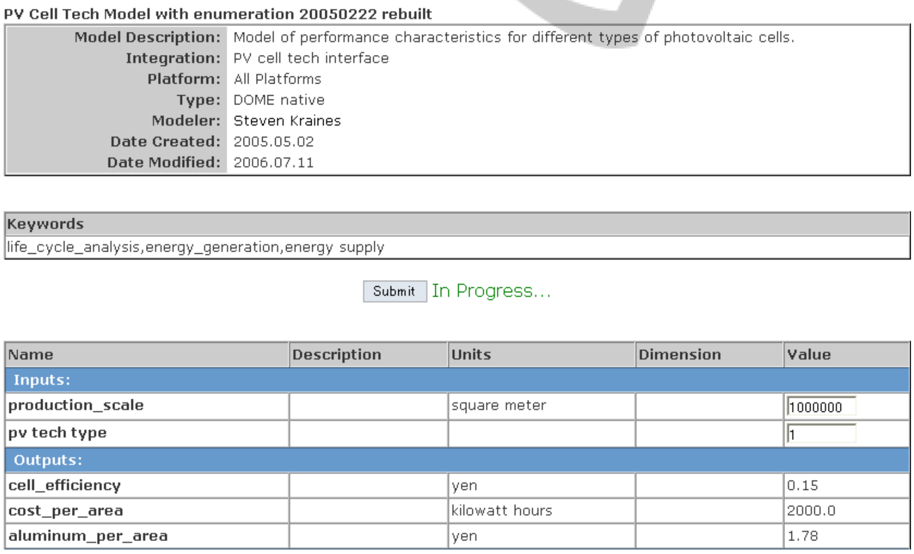
Member: Kraines, Steven — Region: Tokyo, Honshu — View: Activity View - Expanded — Submit

Kraines, Steven: Tokyo, Honsu

Add urban needs / activities	Contribution to CO2 emissions	path/model/ condition/requirements	technology/policy options to consider
electricity	25%	central power grid electricity demand	centralized electric power systems decentralized electric power syste...
electric appliances	10%		high efficiency appliances
commercial appliances	4%		
office building appliances	3%		
residential appliances	3%	lifestyle	
industrial/manufacturing	5%	manufacturing infrastructure	manufacturing process improvement
lighting	10%	building floor area solar irradiation	daylight savings high efficiency lighting
commercial lighting (!)	4%		passive lighting
office building lighting	3%		passive lighting
outside lighting	2%		
residential lighting	2%	lifestyle	passive lighting

Fig. 4. "CO_2 Tech Table" view showing major urban needs and activities of interest to a particular user indexed to the types of models and datasets thought to be required for evaluating that need and the technology and policy options being considered by the user to fulfill the need.

When a user publishes a computational model such as a simulation or database to the web platform, the user can create input and output fields corresponding to the DOME objects described by the model interface, as shown in Fig. 5. The input fields are editable, so that other users may enter values into these fields to express the conditions for model calculation that reflect the particular scenario being studied.



PV Cell Tech Model with enumeration 20050222 rebuilt

Model Description:	Model of performance characteristics for different types of photovoltaic cells.
Integration:	PV cell tech interface
Platform:	All Platforms
Type:	DOME native
Modeler:	Steven Kraines
Date Created:	2005.05.02
Date Modified:	2006.07.11

Keywords
life_cycle_analysis,energy_generation,energy supply

Submit In Progress...

Name	Description	Units	Dimension	Value
Inputs:				
production_scale		square meter		1000000
pv tech type				1
Outputs:				
cell_efficiency		yen		0.15
cost_per_area		kilowatt hours		2000.0
aluminum_per_area		yen		1.78

Fig. 5. Web page showing the basic view of one of the DOME models interfaced to the CO_2 Tech Table collaboration platform.

We have developed a server daemon for the web platform that listens for changes made to the model parameters and executes the actual computational models through the DOME software infrastructure. Results are returned by DOME to the server daemon, which then passes the results back to the user interface. A schematic diagram of the software system is shown in Fig. 6.

In addition to the basic web page view that is provided by the collaboration platform for the models that have been registered to the site, customized layouts including dynamic graphing functionality can be created for particular models, so that data returned from the DOME simulation model servers can be rendered as various kinds of graphs. We have implemented custom interfaces for several models, including the "Residential Building Energy Conservation Model" described in this paper.

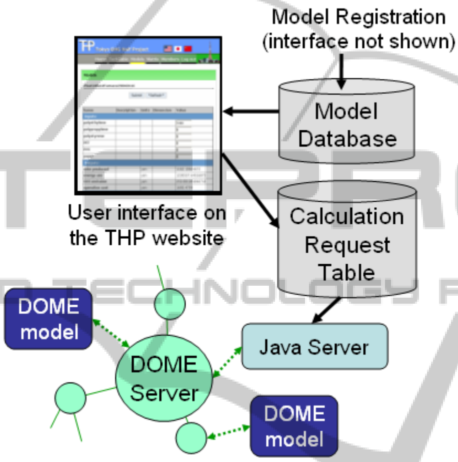


Fig. 6. Schematic diagram of the software system linking the collaboration platform web site to the DOME model integration infrastructure.

4 Discussion

We have been using the DOME modeling integration architecture to construct systems of computational models for studying a number of urban ecosystem processes [9], [10], [11], [12], [13], [14]. While the model integration approach has enabled us to draw together a wide range of expert knowledge from researchers in different academic domains, we have encountered several reoccurring problems when actually trying to integrate computational models that have been developed by different researchers for different research objectives. Because the actual task of integrating two computational models consists of connecting their interfaces, interface design is critical. Of course, multiple interfaces can be created for a single computational model to satisfy different integration needs. Furthermore, specification of units and dimensions for the interface parameters together with the ability of DOME to perform unit conversions and build simple bridge models between interfaces helps to address many of the classical issues of model integration resulting from both structural and semantic gaps between models.

However, one of the most difficult problems that we have had in creating integrated systems of computational models concerns not gaps between interfaces, but overlap. Particularly in creating a model of a complex system, a modeler often feels compelled to include all important aspects of the system being modeled, even if many of those aspects are actually out of the scope of the modeler's expertise. In many cases, we have found it necessary to identify what to "cut out" of a model in order to limit its scope to the part of the system that it is intended to represent. For example, we had to remove the transformation of electricity use in the "Residential Building Energy Conservation Model" to CO_2 emissions in order to integrate that model with the "Power Planning and Dispatch Model". More attention by modelers to clearly define the scope of their computational models would help to increase the general reusability of the models and facilitate the conceptual tasks of integrating them with other models.

The afore-mentioned problems have obvious counterparts in classical software engineering, and it is the author's hope that this workshop will offer an opportunity for exploring those relationships and discovering important lessons to be learned.

5 Conclusions

Methods that leverage cutting edge Information and Communication Technologies are urgently needed to help experts from different research domains to integrate their respective expert knowledge in order to carry out comprehensive analyses of complex system problems such as integrated environmental assessments of combinations of new policies and technologies for urban ecosystem sustainability. The DOME software provides a web-based infrastructure for meeting this need. In the paradigm that we are pursuing, knowledge is expressed in the form of computational models [2]. These computational models are made available over the Internet using the DOME software, much the same way that web servers make html web pages available on the World Wide Web [8]. Furthermore, like with hypertext links in the conventional World Wide Web, computational models distributed on different DOME servers around the world can be integrated by connecting the model input and output parameters in order to form integrated model projects that can be used for conducting comprehensive assessments of complex system behaviors. This paper has discussed some of the technical issues involved in doing this kind of model integration and the solutions that we have adopted.

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