Developing a New-Generation Building Simulation Tool in the United States

D. B. Crawley L.K. Lawrie C. O. Pedersen R. J. Liesen

D. E. Fisher R. K. Strand R. D. Taylor F. C. Winkelmann

W. F. Buhl A. E. Erdem Y. J. Huang

ABSTRACT

In 1995, the U.S. Department of Energy (DOE) began planning for a new generation of building simulation tools. As part of this planning activity, DOE created an inventory of DOE-sponsored tools in early 1996. By mid-1996, this work had evolved into a web-based directory with information on 50 software tools. Today, the directory contains information on more than 125 tools from around the world. To inform the simulation tool planning efforts, DOE sponsored workshops in August 1995 and June 1996, inviting energy simulation developers and users.

After the two workshops, DOE began defining the structure and capabilities of a new building energy simulation tool by building on experience with two well-known programs: DOE-2 and BLAST. Development of the new program, EnergyPlus, started in early 1996 and release is planned for 2000. EnergyPlus is intended to replace both DOE-2 and BLAST. EnergyPlus will include innovative simulation features including variable time steps, built-in and external modular systems integrated with a heat and mass balance-based zone simulation, interzone airflow, and new ground heat transfer modules. This paper describes the structure of the web-based tools directory, the results of the two workshops, the capabilities and structure of EnergyPlus, and DOE's future plans for building simulation tools development.

INTRODUCTION

Many building energy simulation programs developed around the world are reaching maturity. Many use simulation methods (and even code) that originated in the 1960s. Without substantial redesign and restructuring or even rewriting of the programs, it will be difficult, time-consuming, and prohibitively expensive to continue to expand their capabilities. However, recent phenomenal advances in analytical methods and computational power have increased the opportunity for significant improvements in the flexibility and comprehensiveness of these tools. Because of these limitations and opportunities, DOE began planning for a new generation of simulation tools in 1995.

DOE decided to follow a three-step process:

- create an inventory of existing DOE-sponsored tools,
- sponsor workshops to get recommendations from users and developers about needs in energy simulation, and
- define new-generation tools based on the recommendations from the workshops and experience in developing BLAST (BLAST Support Office 1992) and DOE-2 (Winkelmann et al. 1993).

The inventory of DOE-sponsored tools evolved first into a printed *Building Energy Tools Directory* (Crawley 1996) and later into the web-based directory described below. The major input to the planning efforts for new simulation tools were two workshops sponsored by DOE in August 1995 and June 1996. With the recommendations from the two workshops, DOE began formulating plans for a new simulation program, EnergyPlus. DOE envisioned developing an entirely new program working with the developers of the two existing federal government-sponsored programs—Lawrence Berkeley National Laboratory (LBNL), developers of DOE-2 (Winkelmann et al. 1993), and U.S. Army Construction Engineering Laboratory (CERL) and the University of Illinois

D. B. Crawley is a program manager at the U.S. Department of Energy. **L. K. Lawrie** is with the U. S. Army Construction Engineering Research Laboratory. **C. O. Pedersen, R. J. Liesen, D. E. Fisher, R. K. Strand,** and **R. D. Taylor** are at the University of Illinois. **F. C. Winkelmann, W. F. Buhl, A. E. Erdem,** and **Y. J. Huang** are at Lawrence Berkeley National Laboratory.

(UI), developers of BLAST (BLAST Support Office 1992). This team—UI, LBNL, CERL, and DOE—is developing EnergyPlus. As beta testing begins for EnergyPlus in late 1998, the team will begin planning for next-generation building simulation tools that go substantially beyond the capabilities of simulation programs available today.

BUILDING ENERGY TOOLS DIRECTORY

In 1996, DOE established a directory of building-related energy software tools on the worldwide web:

http://www.eren.doe.gov/buildings/tools_directory/

The directory provides information on more than 150 tools, from research-grade software to commercial products with thousands of users. The common thread for all the software is providing information for sustainable design, improving energy efficiency, or incorporating renewable energy concepts in buildings. The directory is intended to be an impartial clearinghouse, providing consistent information about a broad variety of building software available worldwide.

Many DOE buildings programs develop software tools to help researchers, designers, architects, engineers, builders, code officials, and others involved in the building life-cycle to evaluate and rank potential energy-efficiency technologies and renewable energy strategies in new or existing buildings. The directory, originally in printed form, was intended to provide information about the range of tools available from DOE.

The energy tools in the web directory include databases, spreadsheets, component and systems analysis, and whole-building simulation programs. For each tool in the directory, a short description is provided along with information about expertise required, users, audience, input, output, computer platforms, programming language, strengths, weaknesses, technical contact, availability and cost.

The directory is organized in four categories:

- *Whole-building analysis* (energy simulation, load calculation, renewable energy, retrofit analysis)
- *Codes and standards*
- *Materials, components, equipment, and systems* (envelope systems, HVAC equipment and systems, lighting systems)
- *Other applications* (atmospheric pollution, energy economics, indoor air quality, multi-building facilities, solar/climate analysis, utility evaluation, ventilation/airflow, water conservation, miscellaneous applications)

When a user clicks on a category, a list of tools appears along with descriptive information for each, such as applicability to building life-cycle phase, building type, system, equipment, or other important capabilities. The web-based directory continues to expand (DOE welcomes suggestions on software to include).

NEXT-GENERATION SIMULATION TOOLS WORKSHOPS

DOE sponsored two workshops in 1995 and 1996. Energy simulation developers and expert users were invited to the first workshop (developers workshop) held after the Building Simulation '95 conference in Madison, Wisconsin (Mitchell and Beckman 1995). Energy simulation users and other professionals participated in the second workshop (users workshop) held in Washington, D.C. The primary goal for the workshops was to generate and prioritize ideas for next-generation simulation environments. The scope was defined as simulation of building life-cycle processes that influence energy performance and environmental sustainability. Each workshop was structured with three breakout sessions: applications, capabilities, and methods and structures for the developers workshop and applications, capabilities, and user interfaces for the users workshop. We divided the participants into groups, each facilitated by a member of the EnergyPlus team. The facilitators followed a five-step process for each breakout session: brainwriting, grouping and eliminating duplicate ideas, brainstorming, prioritizing and Pareto voting, and summarizing.

At the beginning of each breakout session, the facilitators described the general subject of the session. Then the groups began "brainwriting"—each workshop participant wrote one idea on a notecard and passed that card to the person on their right. As cards were passed, each person reviewed the card and continued to generate their own new ideas. Brainwriting encourages idea generation through individual creativity and brainpower. After 10 to 15 minutes, each group organized the cards/ideas into general groups and eliminated duplicate ideas. To make sure no important ideas were missed, the groups then spent 10 to 15 minutes brainstorming, working as a group to generate more ideas. After brainstorming, each participant was asked to vote for the top 20% of the ideas (Pareto voting). The groups then rank-ordered the cards from highest priority (most votes) to lowest priorities (fewest votes). Voting provided a relative ordering of the ideas within each group; all of the ideas generated were considered useful and were reported. Last, each facilitator prepared a summary that they presented to the entire workshop at the end of each breakout session.

Workshops Results

After the workshops, the facilitators compiled the concepts into similar categories across the breakout groups. These summary groupings of the concepts and ideas generated in the workshops are presented in Figures 1 through 4. In total, the developers workshop generated 225 ideas for the applications breakout session, 242 ideas for the capabilities breakout session, and 201 ideas for the methods and structures breakout session. The users workshop (with more participants) generated 247 ideas for the applications breakout session, 301 ideas

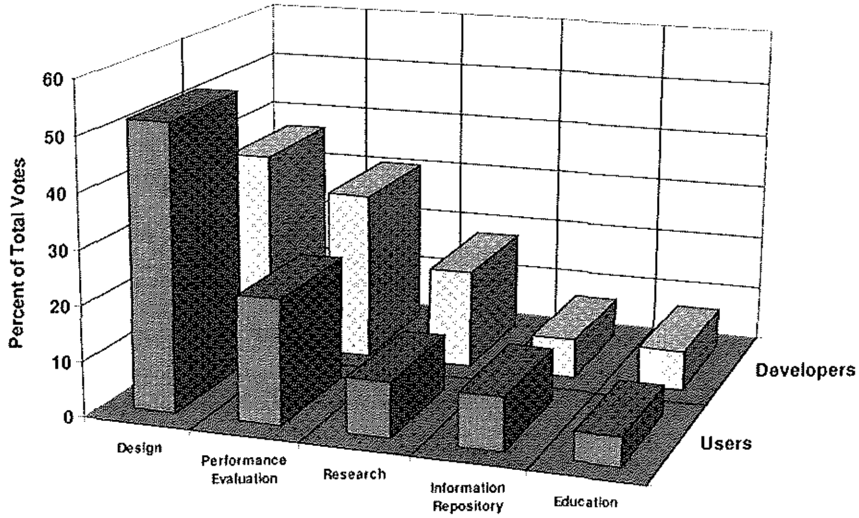

Figure 1 *Program application priorities of developers and users.*

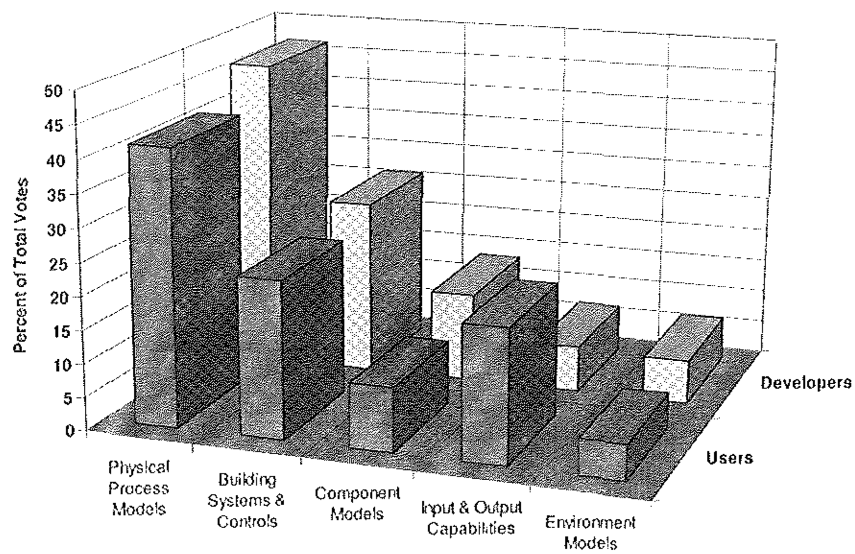

Figure 2 *Program capability priorities of developers and users.*

for the capabilities breakout session, and 213 ideas for the user interface breakout session.

Figure 1 compares the application priorities of users and developers. The raw votes of software developers and users were normalized and are shown as percentages. The developers workshop included researchers in the field of building simulation and energy analysis. Predictably, users disagreed with developers on the importance of research. The significance placed on design by the user community was also not surprising. Although the expected bias of the two groups is discernible, there is remarkable agreement on program application priorities. This indicates that, for the most part, researchers and developers are cognizant of the needs of the user community.

A similar trend can be seen in Figure 2, which compares the capability priorities of users and developers. For the most part, developers seem to be aware of user concerns and priorities. The most serious disconnect occurs on the issue of input and output capabilities. This category was clearly a high priority for users but a lower priority for developers.

As shown in Figure 3, users' top priorities for software program interfaces were interoperability and integration with other building tools such as CAD, and customizability. Still important, but with less agreement as to relative importance, was graphical input/output, defaults/error checking/help, and data storage. One "fun"concept that came from one of the user teams was a TUI, similar to GUI (graphic user interface) but, instead, a telepathic user interface—at least some of the participants were willing to think outside the box.

In Figure 4, the developers' top priorities for program methods and structures are shown. By far the most important issue for the developers was pre- and post-processing meth-

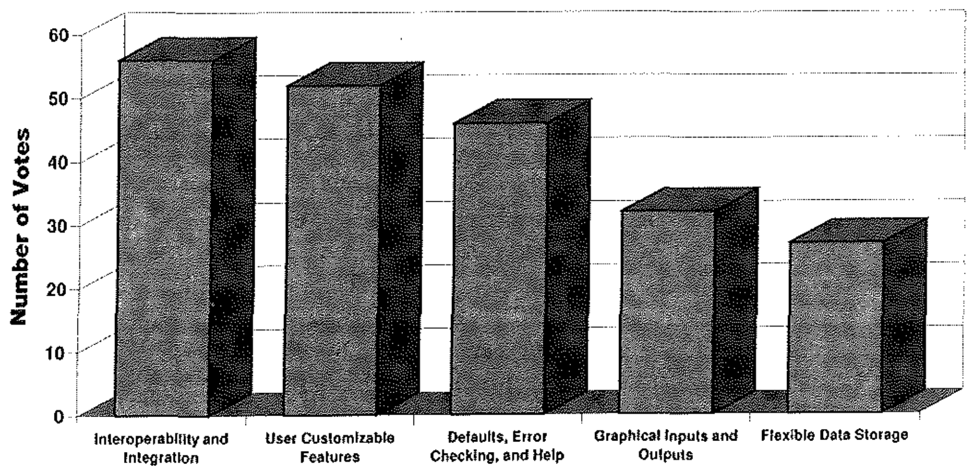

Figure 3　*Program interface priorities of the Users Workshop.*

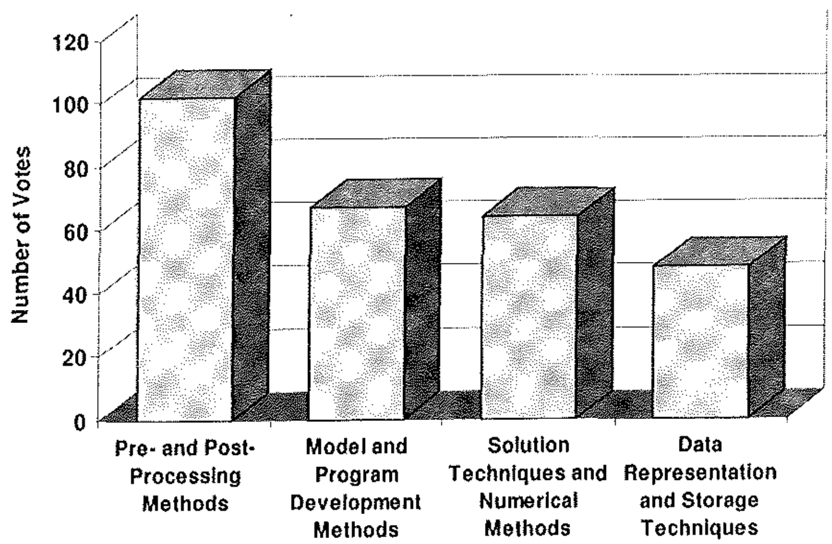

Figure 4　*Program methods and structures priorities of the Developers Workshop.*

ods, similar in importance to the users' priorities of interoperability and integration. The other three categories were considered important but of lesser priority. The authors conjecture that this occurred because developers have solutions, if not time and resources, to solve these areas of concern.

Tables 1 through 4 show the top topics within each category in order by highest number of votes from the users and developers workshops. Tables 3 and 4 (as with Figures 3 and 4) show information only for the users and developers workshops, respectively.

A surprising outcome of the workshops (at least for the authors) was that not many new or unusual ideas were suggested, even with a group of international building energy simulation developers and users. The hundreds of ideas generated during the workshops showed instead that the field of building energy simulation has many fundamental issues that still must be addressed. Program developers were not willing to stretch the boundaries and capabilities of simulation (even in their own minds) until more basic issues are better handled. Some of more highly rated issues include controls, flexible systems and plant modeling, and occupant comfort.

ENERGYPLUS, COMBINING BLAST AND DOE-2

For the past 20 years, the U.S. government has maintained and supported two building energy simulation programs, DOE-2 and BLAST. DOE-2, supported by DOE, has its origins in the Post Office program written in the late 1960s for the U.S. Post Office. BLAST, supported by the U.S. Department of Defense (DOD), has its origins in the NBSLD program developed at the U.S. National Bureau of Standards (now the National Institute of Standards and Technology) in the early 1970s. The primary difference between the programs is the underlying method for calculating zone loads—DOE-2 uses a room weighting factor approach, while BLAST uses a heat balance approach.

TABLE 1
Program Application Priorities of Developers and Users

Developers	Votes	Users	Votes
Design			
Developers	**Votes**	**Users**	**Votes**
Collaborative, integrated, facilitated building design	39	Envelope design	37
Building code compliance—energy and environmental impact	18	Early analysis of design alternatives	25
System selection and equipment sizing wizards	16	Environmental impact and sustainability	24
Lighting/daylighting (selection of products, performance assessment)	7	Economic and cost analysis	15
Aid in selecting retrofit strategies	7	System design	14
		Occupant comfort and safety	11
		Retrofit design	3
Performance Evaluation			
Developers	**Votes**	**Users**	**Votes**
Comfort evaluation	21	Performance contracting	16
Economic, life-cycle, and cost-benefit analysis	14	Code development and compliance	11
Optimal operation and control	14	Performance data acquisition and analysis	8
Control strategies/ optimization/ supervisory	13	Commissioning	7
Indoor air quality	12	Comfort- and energy-based controls	7
		Fault detection and diagnostics	7
Research			
Developers	**Votes**	**Users**	**Votes**
Policy formation code development	9	Emerging technologies and new processes	11
Solution of inverse problem to calibrate model for existing building	6	Occupant health and productivity	8
Basic research	5	Environmental impact	6
Sensitivity and error analysis	5		
Provide basis for simplified	4		
Information Repository			
Developers	**Votes**	**Users**	**Votes**
Electronic owner's manual (building life-cycle)	9	Performance databases and libraries	12
Feed intelligent database for future designs	5	Design databases and libraries	8
Need for structural libraries of models, object-oriented programming	3	Expert systems	4
No gap between description and behavior, i.e., performance data immediately after object selection	2		
Use of historical data files, previous work/buildings	2		
Education			
Developers	**Votes**	**Users**	**Votes**
Student and practitioner education	23	Student education	13
Make it fun	2		

TABLE 2
Program Capability Priorities of Developers and Users

Physical Process Model			
Developers	**Votes**	**Users**	**Votes**
Airflow modeling	25	Envelope/environment interaction	47
Moisture absorption/desorption in building materials	17	Heat transfer models	37
1-, 2-, and 3-D transient conduction	15	Air infiltration and movement within spaces	22
Daylighting	14	Realistic simulation time steps	7
Full generality 3-D shading, lighting, and solar geometry	14	Moisture	7
		Indoor air quality	5
Building Systems and Controls			
Developers	**Votes**	**Users**	**Votes**
Flexible system and plant modeling	18	Intergrated Systems with modular component models	21
First principles system and plant models	14	Realistic building and HVAC simulation	18
Imperfect mixing of zone air	13	Process (e.g., moisture, daylighting) and component controls	12
Zones, systems, plants coupling	8	Performance, compliance and validation	10
Passive and active solar	6	Multiple building systems	7
		Human interaction models	3
Component Models			
Developers	**Votes**	**Users**	**Votes**
Advanced fenestration	11	Air delivery system component models	10
Energy storage in buildings including phase change	8	Central plant equipment models	10
Advanced lighting system modeling	4	Building envelope component models	7
Dynamic coil models	3	Multilevel component models	2
Duct losses	3		
Input and Output Capabilities			
Developers	**Votes**	**Users**	**Votes**
Variable time step	5	Flexible inputs and outputs	26
Uncertainty analysis	4	Life-cycle and real-time cost analysis	11
Economic Analysis	3	Expert systems	7
Costs based on utility rate schedules, modular interchangeable features	2	Optimization	7
Shell to facilitate the combining of components into a system	2	Access library and database information	4
		Design support	3
		Multi-platform, parallel processing	2
Environment Models			
Developers	**Votes**	**Users**	**Votes**
Occupant comfort	9	Pollution models and environmental impact	6
Typical, extreme, and site-specific weather	5	Daylighting	6
Wind pressure distribution	4	Micro and macro weather data	4
Modeling of terrain and surrounding obstructions	2		
Long-term climates with special peak conditions and microclimates	1		

TABLE 3
Program Interface Priorities of Users

Interoperability and Integration	
Users	**Votes**
Interoperable with other tools	22
Interoperable with CAD programs	20
Integration of components and analysis modules	10
Multi-platform applicability	4
User Customizable Features	
Users	**Votes**
Multilevel inputs	13
Simple input options	13
Clear separation of interface and computational engine	10
Customizable output and reports	7
Customizable interface	6
Adaptable to multiple uses	3
Defaults, Error Checking, and Help	
Users	**Votes**
Context sensitive and "smart" help	17
Knowledge-based analysis of inputs and output	10
Automated error and range checking	7
Tutorials and documentation	7
On-line support	5
Graphical Input and Output	
Users	**Votes**
Graphical representation of inputs	12
Graphical output of results	10
Three-dimensional spatial displays	10
Flexible Data Storage	
Users	**Votes**
Component libraries	16
External databases and manufacturer's catalogs	11

TABLE 4
Program Methods and Structure Priorities of Developers

Pre- and Post-Processing Methods	
Developers	**Votes**
Adaptable interface according to user type and stage of design process	21
Knowledge-based front end with intelligent defaults	15
Visualization of complex outputs, including virtual reality display	10
CAD integration	7
Validation by empirical, analytical, and comparative techniques	7
Model and Program Development Methods	
Developers	**Votes**
Object-oriented representation	12
Model reduction	6
Modularity of components	6
Equation-based models-NMF format	5
Tool able to be used by a team (concurrency)	5
Solution Techniques and Numerical Methods	
Developers	**Votes**
Simultaneous solution of loads plant and controls	5
Stochastic methods	5
Macroscopic airflow modeling (non-CFD)	4
Numeric nodal approach for maximum future flexibility	4
Powerful differential-algebraic equation solvers	4
Data Representation and Storage	
Developers	**Votes**
Extensive and extensible libraries of building components and systems	13
On-line documentation, structuring information	6
Flexible structure to allow quick change in systems configuration	5
Standardized data structures	5
Case studies database for decision making	4

The need for two separate government-supported programs has long been questioned. Discussions on merging the two programs began in earnest in April 1994 with a DOD-initiated meeting. No concrete plans came out of that meeting. In 1996, under the initiative of DOE, a project began to develop a new program, EnergyPlus, that merges the best features and capabilities from BLAST and DOE-2. The overall structure for EnergyPlus is shown in Figure 5.

One of the main goals for the EnergyPlus development effort has been to create a well-organized, modular program structure that allows easy addition of new features and/or links to other programs. Fortran 90 was chosen as the programming language for EnergyPlus because of its inherent modularity and object-based structure. (It also didn't hurt that the team is experienced with Fortran.) New code is being written for all modules; no existing code from either BLAST or DOE-2 will be part of EnergyPlus. But the features and capabilities from BLAST and DOE-2 that make both of them so popular, such as the wide variety of HVAC systems and plants, input func-

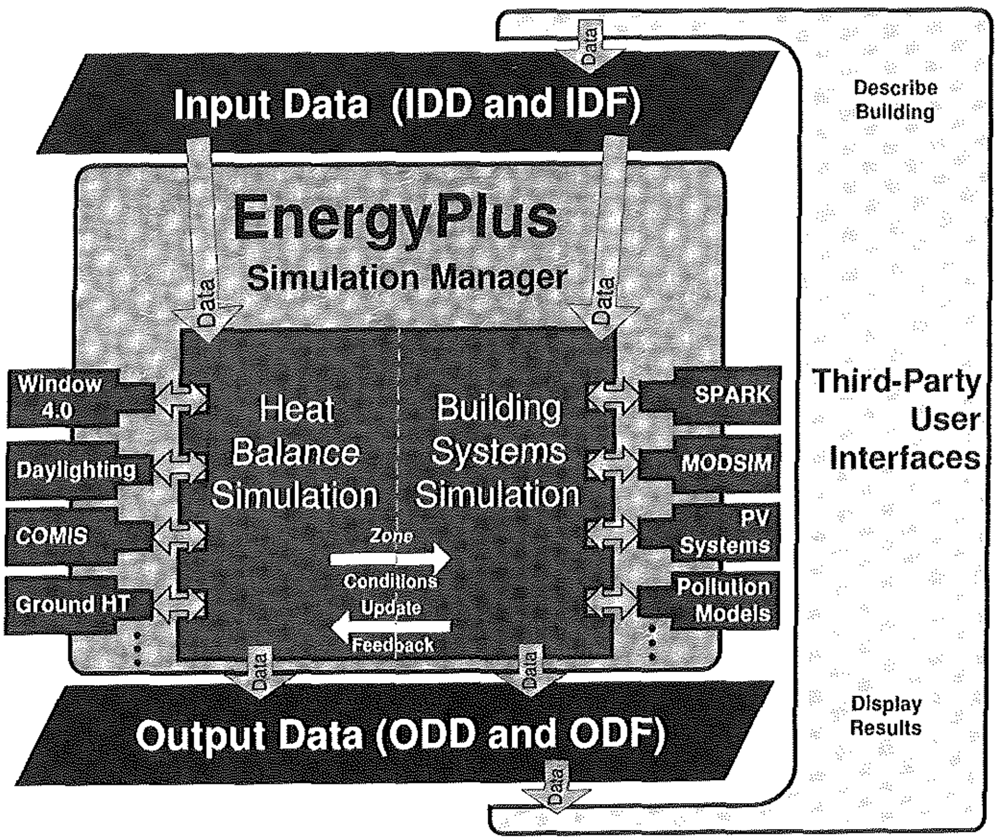

Figure 5 EnergyPlus structure.

tions, and daylighting, have been modularized and reengineered to develop new modules.

The major concept behind EnergyPlus is to combine the heat and mass balance simulation capabilities of IBLAST (Taylor et al. 1990, 1991), a version of BLAST with integrated building, system, and plant simulation, with a generalized building systems simulation manager. In addition to the basic heat balance engine from IBLAST, three new modules have been created based on capabilities within DOE-2: daylighting and electric lighting illumination (Winkelmann and Selkowitz 1985), WINDOW 4-based fenestration (Arasteh et al. 1994), and anisotropic sky.

The daylighting module calculates hourly interior daylight illuminance, glare from windows, glare control, and electric lighting controls (on/off, stepped, continuous dimming) and calculates electric lighting reduction for the heat balance module. In the future, the daylighting module will include an improved interior interreflection calculation, light shelves, roof monitors, and reflection from neighboring buildings. The fenestration module includes capabilities from WINDOW 4: accurate angular dependence of transmission and absorption for both solar and visible radiation and temperature-dependent U-factor. Users can enter a layer-by-layer window description or choose windows from the library (conventional, reflective, low-e, gas fill, electrochromic). Also simulated are movable window blinds (taking into account interreflection of solar and visible radiation between slats) and electrochromic glazing. In the near future, the algorithms will be upgraded to the WINDOW 5 algorithms for coatings and framing elements. The sky model includes nonisotropic radiance and luminance distribution throughout the sky based on the empirical model by Perez et al. (1990, 1991) as a function of sun position and cloud cover. This nonuniform radiance distribution improves calculation of diffuse solar on tilted surfaces (walls and sloped roofs). Through the heat balance simulation module, EnergyPlus will link to COMIS (Fuestel 1990) for improved multizone airflow, infiltration, and ventilation calculations.

The building systems simulation manager controls the simulation of HVAC and electrical systems, equipment, and components and updates the zone air conditions. EnergyPlus does not use a sequential simulation method (first building, then air distribution system, and then central plant) as found in DOE-2 and BLAST since this imposes rigid boundaries on program structures and limits input flexibility. Integrated simulation models capacity limits more realistically and tightly couples the air and water side of the system and plant. Modularity is maintained at both the component and system level. This eases adding new components and flexibly modeling system configurations, and, at the system level, equipment and systems are clearly connected to zone models in the heat balance manager.

To implement these concepts, we use loops throughout the building systems simulation manager, primarily HVAC air and water loops. Loops mimic the network of pipes and ducts found in real buildings and eventually will simulate head and thermal losses as fluid moves through each loop. Unlike BLAST and DOE-2, EnergyPlus has no hardwired "template" systems. Instead, input file templates were developed for the each of the major system types in BLAST and DOE-2. These templates provide an easy starting point for users with system configuration that differ from "default" configurations.

In the longer term, EnergyPlus users will have more systems and equipment options through a link to SPARK (Buhl et al. 1993), a new equation-based simulation tool. SPARK is a better solver for complex iterative problems and is currently in beta testing. SPARK already has a library of HVAC components based on the ASHRAE primary and secondary toolkits. EnergyPlus will continue to have system types (in input file templates), but developers and advanced users will be able to easily build complex new HVAC models with SPARK.

Through translator utilities, DOE-2 and BLAST users will be able to convert existing input files to the new EnergyPlus input file format. Input for EnergyPlus is much simpler than either DOE-2 or BLAST—a simple text file with comma-separated data. Each input line begins with an object name (such as WALL, ROOF, WINDOW, CHILLER, or BOILER) and is followed by data for characteristics (such as size, orientation, zone, or thermal values). We should note again that EnergyPlus has no interface—it is a calculation engine. To ensure that user interfaces are available for EnergyPlus, the team is working closely with third-party user interface developers, facilitating their transition from other simulation programs. The private sector has been more successful in developing user interfaces that meet the needs of their customers. For example, there are currently seven different interfaces available for DOE-2 (which is also only a simulation engine).

The International Alliance for Interoperability (IAI) is developing a de facto international standard, called Industry Foundation Classes (IFC) (Bazjanac and Crawley 1997), for sharing information among building-related software such as CAD, energy tools, facility management, and cost estimating. Once the IFC are available, EnergyPlus will use an IFC-compliant object-oriented data store as the main program interface.

The first release of EnergyPlus is scheduled to begin beta testing in 1999. Future capabilities already planned include improved gas cooling simulation, electrical system simulation, photovoltaic and solar thermal system, and fuel cell modules, among others. Up-to-date information on EnergyPlus can be found on a web site (see "Web Resources" below).

SUMMARY

Participants in the two next-generation simulation tools workshops identified similar topics of concern and priority. Using any simulation program for design is high on both lists (though naturally a stronger issue for users who are typically designers). The main differences appear in the areas where we split the focus of the workshops, interface, and methods and structures. The users workshop participants sent a clear message—user interfaces are crucial to the success of any next-generation tool in the building simulation area.

As seen in Tables 1 through 4, recurrent themes for users were design, environment, economics, and occupant comfort and safety. Designers need tools that provide answers to very specific questions during design. They are less concerned with the mechanics of the tools, although they want tools that provide the highest level of simulation accuracy and detail reasonably possible. The developers focused more on model and module development and related issues. From the similar priorities identified, it is clear that the developers at least recognize the concerns of their users. The authors hope that the information gathered in the workshops will be a catalyst for closer interaction between simulation developers and their users. All the ideas generated during the workshops are available from a workshop web site (see "Web Resources" below).

Although the recommendations from the workshops emphasize the critical nature of user interface for the success of any simulation tool, we should reiterate that EnergyPlus is the heart of a new simulation tool—the calculation engine—and does not come with an user interface. The EnergyPlus team consciously incorporated the calculation capability priorities from the workshops in our development effort (many can be seen in Figure 5).

Next Steps

Late in 1999, DOE will begin formulating a plan for developing a true, next-generation, building energy simulation tool. The plan will outline development of software that goes substantially beyond the capabilities of currently available tools with a broader scope in the building simulation arena (more than just energy). In addition to helping to define the first release of EnergyPlus, the recommendations from the two workshops will be used to set priorities for applications, capabilities, methods and structures, and interface concepts in the next-generation tools. It is DOE's goal to structure development of the next-generation tools as an open process so that a number of contributors from the United States and other countries can and will participate.

REFERENCES

Arasteh, D.K., E.U. Finlayson, and C. Huizenga. 1994. Window 4.1: Program Description. Lawrence Berkeley National Laboratory Report no LBL-35298. Berkeley, Calif.: Lawrence Berkeley National Laboratory.

Bazjanac, V., and D.B. Crawley. 1997. International Alliance for Interoperability: The implementation of industry foundation classes in simulation tools for the building industry. In *Proceedings of Building Simulation '97*, Vol. I, pp.203-210, September 1997, Prague, Czech Republic, IBPSA.

BLAST Support Office. 1992. *BLAST 3.0 users manual.* Urbana-Champaign, Illinois: BLAST Support Office, Department of Mechanical and Industrial Engineering, University of Illinois.

Buhl, W.F., A.E. Erdem, F.C. Winkelmann, and E.F. Sowell. 1993. Recent improvements in SPARK: Strong-component decomposition, multivalued objects and graphical editors. In *Proceedings of Building Simulation '93*, pp. 283-289, August 1993, Adelaide, South Australia, Australia, IBPSA.

Crawley, D.B., ed. 1996. *Building energy tools directory.* U.S. Department of Energy, Renewable Energy and Energy Efficiency, Office of Building Technology, State and Community Programs, June 1996.

Fuestel, H.E. 1990. The COMIS air-flow model—A tool for multizone applications. In *Proceedings of the 5th International Conference on Indoor Air Quality and Climate*, Vol. 4, pp. 121-126.

Mitchell, J.W., and W.A. Beckman, eds. 1995. *Proceedings of Building Simulation '95*, Madison, Wisconsin, August 1995, IBPSA.

Perez, R., P. Ineichen, R. Seals, J. Michalsky, and R. Stewart. 1990. Modeling daylight availability and irradiance components from direct and global irradiance. *Solar Energy*, Vol. 44, pp. 271-289.

Perez, R.R., P. Ineichen, E. Maxwell, F. Seals, and A. Zelenda. 1991. Dynamic models for hourly global-to-direct irradiance conversion. In 1991 *Solar World Congress: Proceedings of the Biennial Congress of the International Solar Energy Society*, Vol. 1, part II, pp. 951-956.

Taylor, R.D, C.E. Pedersen, and L.K. Lawrie. 1990. Simultaneous simulation of buildings and mechanical systems in heat balance based energy analysis programs. In *Proceedings of the 3rd International Conference on System Simulation in Buildings, December 1990, Liege, Belgium.*

Taylor R.D., C.E. Pedersen, D.E. Fisher, R.J. Liesen, and L.K. Lawrie. 1991. Impact of simultaneous simulation of building and mechanical systems in heat balance based energy analysis programs on system response and control. In *Proceedings of Building Simulation '91, August 1991, Nice, France.*

Winkelmann, F.C., and S.E. Selkowitz. 1985. Daylighting simulation in the DOE-2 building energy analysis program. *Energy and Buildings*, 8, pp. 271-286.

Winkelmann, F.C., B.E. Birdsall, W F. Buhl, K.L. Ellington, A.E. Erdem, J.J. Hirsch, and S. Gates. 1993. *DOE-2 Supplement, Version 2.1E.* LBL-34947, November 1993, Lawrence Berkeley National Laboratory. Springfield, Va.: National Technical Information Service.

Web Resources

Building Energy Tools Directory, a directory of information on more than 150 energy tools from around the world.

http://www.eren.doe.gov/buildings/tools_directory/

Next-Generation Simulation Workshops, description of the process and the results from two workshops on needs for new energy simulation tools.

http://www.eren.doe.gov/buildings/energy_tools/workshops.htm

EnergyPlus, up-to-date information on the current status of EnergyPlus and working with the team and documentation such as input data structure, output data structure, and licensing opportunities.

http://www.eren.doe.gov/buildings/energy_tools/energyplus.htm