DEFINING THE METHODOLOGY FOR THE NEXT-GENERATION HOT2000™ SIMULATOR

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ABSTRACT

This paper presents the process followed for defining the features of the next-generation HOT2000 simulator, and the conclusions drawn at the workshops, concerning the most appropriate modelling approaches. It also summarizes the survey of existing programs, and presents the rational for the selection of the starting point for the HOT2000 simulator.

INTRODUCTION

The HOT2000 program for residential energy analysis grew out of the National Research Council of Canada's HOT-CAN program. HOT-CAN used a monthly heat-balance model whereas the current version of HOT2000 utilizes a monthly bin method. Fifteen years ago, the main motivators for a bin-based model -as opposed to a true simulation model - were CPU speed, CPU cost, and disk-storage requirement (for climate data). However, with modern desktop computers, CPU speeds and disk-storage have - and will continue to - increase at astronomical rates, while costs have plummeted. A bin model can no longer be justified for CPU and disk-storage reasons. Additionally, developing new models for bin programs is generally more difficult and expensive as these are often based on regressions of data generated from multiple parametric runs using more powerful modelling systems. Finally, new technologies are being developed that require scheduling (such as integrated mechanical systems) and many utilities are implementing time of day rates - features that a bin model cannot handle.

For these reasons, Natural Resources Canada (NRCan) has begun the development of a simulation-based engine (ie. a time-step model in which time is the independent variable), a project referred to as the "Next-Generation HOT2000 Simulator." The prime purpose of the new program will remain the estimation of annual energy consumption. However, users will expect the tool to serve other modelling tasks in the near-term.

This paper describes the process undertaken to determine the types of models that should be incorporated in the new simulator and to select a starting point program from which to begin development of the next generation simulator.

CONTEXT

Any program must be designed around its users' needs. Although this project does not address the user interface, it is critical that the models selected for the simulator not demand data that users cannot provide.

HOT2000 is used for modelling low-rise residential buildings: single-family houses, semi-detached houses, and row houses. It is primarily used to estimate annual energy consumption and the energy impact of design options. It is also used for demonstrating conformance with the Canadian R-2000 HOME Program™, the Canadian EnerGuide for Houses Program and will soon be used for demonstrating compliance with the Model National Energy Code for Houses of Canada.

The primary users of HOT2000 are architects, engineers, builders, auditors and energy analysts and researchers. They typically have a practical knowledge of building science but limited familiarity with simulation methods. For these users, simplified data entry is a priority. A direct mapping between their knowledge of a building's physics and data inputs is essential. For example, users can be expected to give a detailed description of an envelope construction, including framing details. However, they cannot be expected to describe air-leakage paths, discharge coefficients of air-flow openings, or to select between free-convection surface-heat-transfer correlations.

Although CPU speeds are a less dominant factor in designing simulation programs than they were in the 1970s and 1980s, run times will still be a factor for users. Some users will perform batch simulations to assess a number of energy conservation upgrades, for example. Therefore CPU requirements must be considered as a factor in this project along with accuracy, ease-of-implementation and the users' needs.

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METHODOLOGY

A multi-stage process was utilized to determine the selection of the starting point software for the next generation simulator:

1) An extensive review of technical literature was performed to identify existing mathematical models for simulating building-side processes.[2]

2) A day-long workshop was held with topic-area experts to discuss and debate which building-side processes should be considered in the simulator and to identify the appropriate modelling resolution and modelling approaches to simulate each of these processes. [3, 4]

3) An extensive review of technical literature was performed to identify existing mathematical models for simulating HVAC equipment and processes. [5]

4) A day-long workshop was held with topic-area experts to discuss and debate which HVAC processes and equipment types should be considered and to identify the most appropriate modelling resolution and modelling approaches to use. [6, 7]

5) A four-step survey of approximately 30 existing building simulation tools was performed to identify the most appropriate starting point to use for the next-generation HOT2000 simulator. [8, 9, 10]

PHASE 1: BUILDING-SIDE PROCESSES

Phase 1 of this project involved performing a literature survey of modelling methods for all *relevant* building-side processes. In this context, a relevant process is one that must be simulated for the program to meet HOT2000 users' needs currently and looking to the next 15 years. For example:

- heat transmission through opaque envelope components, including impact of thermal bridging,
- direct and diffuse solar insolation, shading, reflection, and absorption,
- infiltration through unintentional and intentional openings, including natural ventilation systems (sensible and latent effects),and
- loads resulting from moisture absorption and desorption.

A report was written summarizing these processes.[2] From the report a list of questions were assembled to guide a one-day experts workshop.[3] The purpose of the experts workshop was to select the *most appropriate* models for building-side processes to use in the new simulator. The list of questions was used to generate debate on each process and to ensure that all processes were considered. Following are a couple of examples of the questions discussed:

- Should a conduction response factor or numerical approach (eg. finite difference) be used for above-grade opaque envelope components?
- Should a weighting factor or heat-balance approach be used to model heat transfer from interior envelope surfaces and internal heat sources (eg. lights, people) to the indoor air?
- Should infiltration be determined with a single-cell model or through an air-flow network?
- Should windows be modelled as single components (ie. overall U-values) or as layered constructions (ie. explicitly model radiation, convection, and conduction). If the latter, how should frames and spacers be treated?

The experts used the following criteria to select the models:

- capability to model the relevant physical processes,
- accuracy,
- ease of implementation,
- ability to integrate HVAC calculation methods,
- CPU requirements,
- flexibility for future improvements,
- interoperability with other tools, and
- data-input requirements

It was not the goal of the workshop to select which methods are the *best* or the *state-of-the-art*, but rather to select which are most appropriate for the given application.

It was agreed that ideally the next-generation HOT2000 simulator should be developed to incorporate the major modelling capabilities presented below.

1) Transient heat transfer through opaque envelope components should be modelled using one-dimensional conduction response factor or numerical approach. The effect of thermal bridging should be taken into account by using modified material properties, based on a simplified approach involving some weighted combinations of parallel-heat-flow and parallel-isotherm approximations.

2) A heat-balance approach should be used to model the heat transfer between:
(i) inside surfaces and the indoor air,

(ii) internal heat sources and the indoor air.

3) The modelling of windows should be treated as rigorously as the opaque components since the solar gains & heat loss through windows can greatly affect the energy use of a house. Heat transfer should be modelled considering the glazing as a multi-layered construction. The radiative, convective and conductive heat flows involving glazing panes, air spaces, frames and spacers should be explicitly modelled, based on a simplified user description. Transmission of solar radiation should be modelled using SHGC and angle-of-incidence modifiers.

4) An anisotropic sky model should be used to determine the directional distribution of diffuse solar radiation. The reflectivity of snow should be modelled as being angularly dependent and a function of the snow age.

5) Window shading by fins and overhangs should be explicitly modelled by using the window and shading device geometry and tracking the sun rays. A simpler approach, using time-varying shading multipliers, should be used for shading by curtains, other parts of the building, other buildings and surrounding trees.

6) Heat transfer through below-grade walls and floors should be modelled, for the foreseeable future, by a frequency-domain response-factor approach. Simplified techniques can be used to account for non-standard geometries. In the long term, the numerical approaches should be used, to allow for explicit modelling of complex foundation geometries and site-specific features. Since high-frequency fluctuations of interior air temperature have little impact on heat losses through the below-grade elements, the calculations should be based on a time-averaged constant basement air temperature.

7) Longwave radiation exchange should be calculated on a time-step basis with a radiosity model. As a detailed geometrical description of the house is required to calculate the view factors, a scheme would have to be developed to default the geometrical description based on a simplified user description. As a simpler alternative, the view factors could be pre-estimated.

8) Surface-convection coefficients should be calculated on a time-step basis using appropriate correlation-based models.

9) The house should be modelled using at least 10 thermal zones. However, for simple analyses, the simulator should be capable of representing the entire living space as a single zone. A one-dimensional transient conduction model should be used for evaluating the heat transfer through interior partitions.

10) The level of thermal mass for each zone should be modelled as a lumped capacitance. However, in the case of zones that experience large temperature swings, such as sun spaces, an accurate description of the area of the mass is important to model the radiation exchange.

11) A nodal air-flow network, coupled with a heat flow model, should be used for modelling air infiltration and inter-zone air flow. There is a great deal of uncertainty regarding the size and location of leakage paths through the exterior envelope. A scheme that defaults leakage paths based on a simplified user description (e.g., airflow rate at 50 Pa from a blower door test) should be developed.

12) Although a one-hour time step is sufficient for estimating the energy consumption in a house, smaller time steps may be required to model:
(i) instantaneous fuel and electrical demands
(ii) some HVAC and control systems, and
(iii) the pollutant dispersal with an air-flow model.

PHASE 2: HVAC-SIDE PROCESSES

Phase 2 of this project followed the same format as Phase 1 (ie. literature survey, workshop) except it concentrated on the HVAC-side processes. Some of the relevant HVAC-side processes and equipment examined in the literature survey were:

- forced-air furnaces,
- baseboard heating with central or distributed thermostats,
- active solar with back-up DHW systems,
- thermal losses from air and hydronic distribution systems,
- heated floor slabs,
- air-side economizers "free-cooling", using dry-bulb or enthalpy control,
- predictive and adaptive controllers

A report was written summarizing these processes[5] and once again a list of questions were assembled to guide a second one-day workshop[6], this time with HVAC experts. The list of questions the experts debated included some of the following:

- Should the scope of the HOT2000 simulator be limited to conventional HVAC systems or should more esoteric systems (eg. evaporative cooling, night-time air purging) be considered?

- Should building loads and HVAC be modelled simultaneously (or at least sequentially on a time-step basis) or separately (building loads predicted for some assumed indoor conditions over entire simulation period and results passed to HVAC simulation)?
- Should transient or steady-state modelling approaches for HVAC equipment be used? In what situations do system dynamics need to be considered? What are the benefits and costs of considering system dynamics?
- To minimize data-input requirements, the HOT2000 interface will require users to describe HVAC at the *system* level (eg. forced-air gas-fired furnace) but the simulator could model at either the *system* (eg. forced-air heat pump cooling system), the *component* (eg. heat pump, fan, ducting), or the *sub-component* (compressor, evaporator, condenser, expansion valve, etc.) level. Which level of modelling resolution is most appropriate for the HOT2000 simulator?

The experts used the same list of criteria to select the most appropriate processes and equipment to be modelled in the new simulator as for the building-side processes. The major recommendations are presented below.

1) It was noted that the building industry is turning its focus to optimizing mechanical systems now that envelope performance is quite advanced. Hence the HOT2000 simulator could become a useful tool for
(i) sizing the equipment of integrated systems, and
(ii) developing alternative system configurations and evaluating their energy performance.

2) It was noted that building thermal loads are generally treated with more rigour than HVAC equipment. The first workshop recommended to favour first-principles approaches for modelling building loads (eg. windows). In the case of modelling HVAC equipment, the user does not always have access to sufficient data to allow a first-principles approach. Hence, the most appropriate model should be selected based on the data available to the user: in one case it could be a correlation-based model developed from the manufacturer's data, and in another case it could be a first-principles model.

3) HVAC equipment should be modelled using a quasi-steady-state approach where the boundary conditions vary in time, but steady-state equations are solved each time step. It was decided that transient modelling of HVAC equipment is not appropriate for the next HOT2000 simulator since, in general, users will not have access to sufficient data to justify this level of modelling resolution.

4) To minimize the data-input requirements, the user will be asked to select a prepackaged HVAC *system* from a given list. However, the simulator will use the *component*-level HVAC modelling to simulate the energy performance. This will make the program more extensible as new technologies are developed, but keep the user input simple.

5) Although it may be acceptable to limit the first release to conventional HVAC systems, the modelling methods should be sufficiently flexible to accommodate, in the near-term, more advanced systems such as gas-charged desiccant cooling, gas fireplace DHW, grey-water recovery or using swimming pools as air-conditioning condensers.

6) The simulator should be able to model
(i) multiple HVAC systems serving one thermal zone (eg. a central forced air system and an electric baseboard heater) and
(ii) separately controlled secondary systems (eg. fan coils).

7) All common control strategies should be modelled (eg. as a function of indoor or outdoor air temperature or time-of-day schedules). The modelling of simplified predictive controls would be adequate for the first version, but more advanced strategies (eg. based on simulated occupant behaviour) should be considered in the future. The selection of modelling methods should take into account the extensibility to accommodate new control systems.

8) The simulator should employ a partitioned solution procedure whereby the equations characterizing building thermal loads and HVAC systems would be coupled but solved separately, perhaps with different time steps. The two solvers would march together in time, exchanging information each time step. An hourly time step may be adequate for simulating the building loads, but this would be too crude for HVAC systems. Short time steps may be required to accurately predict demands and to simulate control systems. However, very short time steps could lead to instabilities in the simulation of building loads. Therefore, a number of small time steps (eg. 5 minutes) could be used on the HVAC-side for each building-load time step (eg. 1 hour). In the case of strong coupling between building loads and HVAC systems, such as radiant-floor heating or dynamic walls, some iterations may be required.

9) The simulator should be able to model the demand for electricity and natural gas using sub-hour time steps. As time-of-use rates and demand charges might become more common for residential customers, some energy management and control strategies should be modelled.

PHASE 3: SELECTION OF THE MOST APPROPRIATE STARTING POINT

It would be unfeasible and undesirable for NRCan to develop a new simulator from scratch. Most of the models selected in Phase 1 and Phase 2 exist, in some form, in existing building simulation programs. The goal of this third phase was to evaluate the technical capabilities, availability of source code and the potential for modification of existing energy analysis programs, in order to select the most appropriate starting point for the development of the HOT2000 simulator. A survey based on a four-level screening process of about 30 existing building simulation tools was performed. Only those programs passing a given screening level were considered at the next level.

It is important to remember that the evaluation of each program was with respect to its appropriateness to the HOT2000 simulator and not a rating of the *best* program on the market.

Level 1: preliminary review of modelling methods
In the first level of surveying, a preliminary review of about 30 energy analysis programs was performed (based on published information and available expertise) to compare their modelling approaches against the recommendations from the two workshops. The following programs were evaluated at this level:

HOT2000	DOE-2	BLAST
EnergyPlus	TRNSYS	ESP-r
ENERPASS	SERIRES	Energy-10
CLIM2000	QUICK	TASE
TARP	TRACE	HAP
ENER-WIN	3TC	Meriwether
HVACSim+	CONTAM	MarketManager
CHEETAH	DEROB-LTH	ASHRAE toolkits
Energy-2	HTB2	TAS
TSBI3	S3PAS	APACHE
HOUSE-II/ASHRAE SP43		

Only existing capabilities of each program were considered in this survey. In the case of EnergyPlus, which builds on the best features of BLAST/IBLAST and DOE-2, *existing* was interpreted to mean capabilities that currently exist in BLAST/IBLAST and DOE-2. Consequently, some features that are planned for the first release of EnergyPlus were not credited in this survey.

In this first level, a subset of the modelling capabilities and approaches recommended at the two workshops were selected, placing emphasis on items that were felt to be fundamental and could be assessed in a broad screening. The 11 items selected were as follows:

- Transient heat transfer through opaque envelope components, using a conduction response factor or numerical approach,
- Heat-balance approach to model the heat transfer between:
  (i)the inside surfaces and the indoor air
  (ii)the internal heat sources and the indoor air,
- Sub-divide the house into at least 10 thermal zones,
- Nodal air-flow network for infiltration and inter-zone air flow, coupled with a heat flow model,
- Heat transfer through glazing considered to be a multi-layer construction, and explicitly modelling the radiative, convective and conductive heat flows involving glazing panes, air spaces, frames and spacers,
- Explicit modelling of window shading by fins and overhangs, by using the window and device geometry, and tracking the sun rays,
- Longwave radiation exchange by radiosity model calculated each time step,
- Surface-convection coefficients calculated each time step,
- Simulation time steps between 5 minutes and 1 hour,
- Building loads and HVAC coupled on a time-step basis, to account for the important interactions between the thermal loads and HVAC system operation.
- Component-level HVAC simulation, in which the component models are assembled to simulate the performance of the HVAC system. The developer/programmer should be able to easily add new component models (for example ducts, heat pump fans) and to create new systems from the components.

A table was created specifying whether each program incorporated each modelling recommendation (as an example, a section of the table is reproduced as Table 1). The quality of the algorithms and the accuracy of the results were not examined at this stage.

Few programs met all 11 criteria. Consequently, the following approach was used to select the programs that would continue on to the level 2 screening:

Table 1 Preliminary review of modelling methods

	Modelling approach	Existing Programs (each number corresponds to a program in the full report)									
		1	2	3	4	5	6	7	8	9	10
a	Transient heat transfer through opaque envelope components	N	Y	Y	Y	Y	Y	Y	Y	Y	Y
b	Heat-balance approach for interior air spaces	N	N	Y	Y	Y	Y	Y	Y	Y	Y
c	sub-divide the house into at least 10 zones	N	Y	Y	Y	Y	Y	N	Y	N	Y
d	Nodal air-flow network for infiltration and inter-zone air flow	N	N	N	N	N	Y	N	N	N	Y

- Any program that did not have a transient model for above-grade envelope components or did not use a heat-balance approach was eliminated.
- Any program that included either a nodal air-flow network or component-level HVAC simulation was passed; these are fairly uncommon and substantial modelling approaches in whole-building programs.
- Of the remaining programs, any which did not have a multi-layer window model or a radiosity model were eliminated.

As a result of this process, 9 programs were moved on to Level 2:

EnergyPlus
TRNSYS
ESP-r
DEROB-LTH
S3PAS
HVACSim+
CLIM2000
HTB2
HOUSE-II/ASHRAE SP43

Level 2: availability, rights to use, technical collaboration and support

The purpose of the level 2 survey was to determine whether it would be possible to actually license the rights to each program and whether technical support would be available. Contact persons were found for each selected program, and two letters were sent: one from NRCan, explaining the goal of the whole project, and the second one from the consultant, containing the survey form. The survey asked the following questions:

a) What is the availability of the program (ie. public domain, proprietary, made available to certain parties)
b) Has the owner all the rights to the program?
c) Could NRCan obtain the source-code rights? Specify requirements and conditions.
d) Could NRCan obtain the derivative works rights? Specify requirements and conditions.
e) Could NRCan obtain the distribution rights? Specify requirements and conditions.
f) If the answers to items (c) through (e) were yes would there be any royalties? What type and how much?
g) Specify other conditions related to the use of the program.
h) Could technical support be provided to NRCan? What would the duration be and what would it cost?
i) Is the owner interested in collaborative work with NRCan in the development of the *Next-Generation HOT2000 Simulator*?

Based on the information received from the Level 2 survey, NRCan moved the following programs on to Level 3:

EnergyPlus
ESP-r
TRNSYS
HOUSE II/ASHRAE SP43
DEROB-LTH
HTB2.

The programs chosen were those for which NRCan could obtain the necessary rights and technical support.

Level 3: technical documentation and source-code structure

The purpose of the Level 3 screening was to determine how the programs are structured and documented. These are key issues in determining whether a program could be used as a starting point for the new HOT2000 simulator. Without good documentation it would be very difficult, if not impossible, to understand and modify the code. Responses to the following issues were required:

a) How the programs are structured,
b) What programming languages and compilers are used,
c) What operating systems and environments are currently supported,
d) If there is detailed documentation describing the

format of data input, output and temporary files,

e) If there is extensive documentation describing the theory of the simulation methodology applied and the corresponding algorithms,
f) If there is documentation describing how the theory has been implemented in the program and describing the overall structure,
g) If there is detailed external documentation and source-code annotations describing the routines,
h) If the program is currently supported and being actively developed,
i) How many organizations and people are involved in the technical support and the development.

A questionnaire was sent to each contact person for the aforementioned programs.

Upon reviewing the level 3 screening results, NRCan moved the following three programs on to Level 4:

EnergyPlus ESP-r TRNSYS.

These three programs possess many of the technical capabilities required for the HOT2000 starting point: they are well documented, and they are the objects of continuing and substantial development efforts. All the programs surveyed possessed certain strengths, however only these three programs matched the needs of the starting point closely enough to warrant the Level 4 in-depth review of modelling methods.

Level 4: detailed review of modelling methods

The goal of this level of screening was to examine the algorithms used by the selected programs (EnergyPlus, ESP-r and TRNSYS) with respect to the recommended modelling approaches for the Next-Generation HOT2000 simulator. For EnergyPlus, since the program is still under development, it was considered to have a particular capability if the model had already been implemented in the program or if the capability existed in one of its parent programs (ie. BLAST or DOE-2). The contact persons for each program were extremely helpful: they reviewed the draft of the final report, and made appropriate comments concerning the actual capabilities.

Once the technical capabilities had been examined in detail, NRCan then assembled a list of criteria to assist in selecting the preferred starting point:

a) Modelling capabilities: solution method, air flow modelling, longwave radiation exchange, integration of loads and HVAC components.
b) Extensibility of HVAC simulation methodologies.
c) Level of effort to develop and incorporate loads models and HVAC models.
d) Timing availability,
e) Technical risk,
f) Potential for future collaborative R&D,
g) Programming language and operating system,
h) Capital and operating cost implications,
i) Documentation available,
j) Licensing and intellectual property rights,
k) Time investment required to learn the starting point program and the code structure.

Rationale for the final selection of the starting point

Although all three programs have impressive technical capabilities and have been developed by equally impressive teams, NRCan selected ESP-r as the preferred starting point for the next-Generation HOT2000 simulator. Following is some of the rationale for why ESP-r was selected.

Modelling capabilities:

ESP-r has the capability to solve the load equations and the HVAC equations simultaneously with the time steps for the load and the plant simulations set at the same value or different. The experts at both workshops felt that these were critical points to modelling their interaction properly.

ESP-r has a *nodal network air-flow model* implemented within the program with full integration between the thermal domain and the airflow domain. The model has existed in ESP-r for 10 years and thus has been thoroughly tested.

The *longwave radiation exchange model* in ESP-r is very detailed. Using calculated view factors between the surfaces of the room, emissivities and the temperatures of the different surfaces, it calculates the longwave radiation exchange.

Extensibility of HVAC methodologies

A component level model for HVAC systems is available in ESP-r. Though ESP-r already contains the most common HVAC components some new components will be required. It is expected that the level of effort to develop and incorporate new HVAC models into ESP-r would be low to medium.

Timing availability

ESP-r is currently available. This was critical since it is important for the NRCan development team to begin work on the new simulator immediately.

Technical Risk

There is low technical risk with ESP-r. It has been around for approximately 20 years and thus is a stable program. It already contains most of the models that are required and thus it is not necessary to wait for them to be developed.

Documentation
There is extensive documentation describing the theory of the simulation methodologies and how the theory has been implemented within ESP-r. The source code is highly structured and extensively commented. Numerous theses describe recent enhancements in detail.

Licensing and intellectual property rights
Source-code rights, derivative works rights and distribution rights are all available to NRCan upon licensing.

Time investment to learn ESP-r
Many of the people on the development team at NRCan have already taken courses on ESP-r. As well, the ESP-r development group offers regular training courses. The course format and material can be tailored to suit the specific needs of the participants. The ESP-r web site also has a tutorial that guides the user through the main features of the program.

CONCLUSIONS

The selection of the starting point for the Next-Generation HOT2000 Simulator was a lengthy process taking an elapsed time of approximately 18 months. However the authors feel that the time spent was very useful both for determining the requirements for the new simulator as well as ensuring that duplication of models that are available in existing programs did not occur.

A web site was set up containing documentation of all of the Phases of this project including the details of the rational for the final selection. The authors can be contacted at ibeausol@nrcan.gc.ca or dhaltrec@nrcan.gc.ca for the web address.

At this point development on the new simulator has begun. It is expected that not all models suggested in the workshops will be incorporated in the first release of the program so that the program can be released within a reasonable amount of time. These models will however, be incorporated in subsequent versions.

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All references for the 30 programs examined during this project can be found in the Task 3 Report. Unfortunately due to limited space they could not be provided here.