UTILIZING BUILDING ENERGY SIMULATION TO IMPROVE PROCESS LOAD HEAT RECLAMATION FOR A MULTI-SPORT ATHLETICS VENUE

Joel Good[1], Bryan Debruyn[2], and Derek Whitehead[1]

[1]Rowan, Williams, Davies & Irwin (RWDI), Vancouver B.C., Canada[*]
[2]Stantec Consulting, Vancouver B.C., Canada

ABSTRACT

Large, multi-use sports and recreational facilities provide a unique, yet challenging, opportunity for energy conservation due to their large process loads. The proposed paper describes the use of building simulation to aid in mechanical system and architectural design to improve heat recovery from process heat generation to satisfy building loads.

The focus of this study is a recreational facility that consists of an NHL-size ice arena, 8-sheet curling rink, a gymnasium, change and restrooms, offices, library, fitness studios, a large glazed atrium, as well as 50 metre lap, leisure, outdoor and whirl pools. The ice plant providing refrigeration to generate and maintain the ice surfaces produces large amounts of waste heat when in operation. Traditionally, ice plant waste heat has been recovered for rink-related hot water loads only (i.e. snow melt pits, ice resurfacer fills for ice resurfacing, and sub-floor freeze protection), with the excess being rejected to the ambient environment. With this project, the proximity of the rinks and pools offers a unique opportunity for a more thorough recovery and reuse of the ice plant's waste heat.

When designing to reuse waste heat, difficulty lies in balancing the availability and grade of reclaimed heat with a corresponding building or process load. To accurately predict this balance, two building energy simulation tools were employed, one to predict building HVAC loads (eQUEST) and a second to describe the system energy flows (TRNSYS). Initially, hourly end-use process loads were determined based on applicable literature and historical data and knowledge gained from similar facilities operated by the regional parks board owner. These loads were then included in a whole-building energy simulation to determine overall HVAC and building energy consumption. A second simulation, specific to the building's mechanical systems, was then used to calculate the dynamics of demand and availability of heat, taking into consideration the grade of heat available from the heat sources (ice plant, solar hot water collectors, heat recovery, and building heating equipment). The results of these complimenting simulations aided in determining the design of the building's mechanical systems including sizing a hot water storage system intended to balance the inherent time lag.

This paper describes the procedure employed to predict the transient nature of athletic facility process loads, the combinination of multiple building simulation tools to predict and balance heating loads with process waste energy, and the necessary integrated design process required.

KEYWORDS

Building Simulation, Process Heat Recovery, Integrated Design Process, Natatoriums, Ice Arenas.

INTRODUCTION

The community & aquatic centre described in this paper is designed for Vancouver, BC, Canada. It will consist of a large community complex containing eight curling sheets, a hockey arena, two large indoor pools, a large whirl pool, and a large outdoor pool, as well as lounges, gymnasiums, change rooms, offices, library, preschool, aerobics and fitness rooms. The purpose of this study is to provide building and mechanical design assistance with the intent of minimizing the overall energy consumption of the facility.

The main challenge in this building design was to effectively incorporate heat recovery from the ice plant and chilled water plant into the building. The design team recognized early on in the design process that an integrated design approach would be required. At the centre of this process was detailed stakeholder consultation and a whole-building simulation model to determine system loads. The loads from this model were then input into a detailed transient energy model that simulated the entire heating and cooling mechanical system. The purpose of this transient energy model was to simulate the behaviour of the integrated system with respect to heat demand, recovered heat availability, thermal storage, cooling demand, domestic hot water demand,

[*] The author performed the studies described here as an employee of Stantec, Vancouver, BC, V6B 6A3, Canada, and gratefully acknowledges Stantec's support.

and solar thermal energy collection. TRNSYS was used to simulate the mechanical systems, and eQUEST was used for the building simulation.

The novelty of this work lies in the large effort employing building simulations within an integrated design process to predict the transient nature of the facility's many heating loads and all potential process heat recovery mechanisms.

Energy Analysis

The goals of the whole building energy analysis are to provide design assistance on components of the mechanical and architectural design. The mechanical design group requested:

- A detailed understanding of the anticipated pool and rink loads,
- Input on the availability and quantity of heat recovery from the ice plant to preheat the hot water systems,
- Requirements and sizing options for possible heat storage to balance the fluctuations of varying amounts of recoverable heat,
- Feedback on the operation and sizing of heat pumps required to upgrade recovered heat to desired operating temperatures,
- Quantifying the potential for heat recovery from exhaust air in the natatorium, curling lounges, and change rooms (for both rink and pool sides),
- Potential of energy savings associated with the installation of carbon dioxide sensors in the curling rink, ice arena, and curling lounges, and
- Impact of operational scheduling on energy consumption (i.e. weighing the heat recovery benefits with the energy consumption inherent with operating a skating rink in the summer months).

As well as mechanical design assistance, a number of other energy conservation measures (ECMs) were investigated for aiding architectural and electrical design decisions. All ECMs were compared with a baseline building as defined by the ASHRAE 90.1-2001 Energy Standard for Buildings. These additional ECMs included:

- Predictions of energy conservation associated with advanced lighting design (i.e. reduced lighting power densities and increased control methodologies), and
- Energy consumption analysis for improved envelope design.

As the study progressed and design strategies emerged, additional studies were requested. These included a detailed investigation into potential solar thermal systems as well as a study of potential natatorium heat recovery strategies.

Building Description Overview

As mentioned previously, the 13,900 m^2 of facility floor area will consist of a wide variety of space types. Anticipating the occupancy schedules and usage of these spaces was aided through consultation with the regional parks board engineers and planners. It was determined that the community centre spaces (offices, library, preschool, multipurpose and fitness rooms) would operate under typical community centre hours and conditions. The curling rink was anticipated to run during the winter months only (typically from September to May) with the space (without ice) being used for multipurpose use in the summer months. Similarly, it was anticipated the ice arena would not be operational during the summer months, although the energy implications of maintaining an ice surface for the entire year and utilizing the associated waste heat were explored with the building modeling simulations. The indoor pools (lap, leisure, and whirl) are anticipated to operate all year round with the exception of the outdoor pool, which will be operational only during the summer months (June to September).

Due to the complex and varied indoor conditions anticipated (from the warm humid air of pools to the cool dry air of the rinks), a good envelope design is necessary to maintain occupant comfort. Recommendations on suitable envelope parameters were made to ensure occupant comfort conditions are met with the concurrent goal of minimizing energy consumption. Glazing percentages, shading coefficients, and U-values as well as varied wall and roof constructions were all considered. Again, the building energy simulations were used to make predictions on envelope designs, the results of which have been provided in the energy conservation measures (ECM) section of this report.

An energy-conscious lighting strategy including low-wattage fixtures and automated control to sense daylighting and occupancy in appropriate spaces was also investigated to reduce the overall lighting power density and energy consumption for the facility.

Building Systems Overview

The building will employ a number of energy efficient strategies with the systems design, including: refrigeration plant heat recovery, domestic hot water preheat, ventilation air heat recovery, high efficiency condensing boilers, and renewable energy considerations.

The community and aquatic centres will share one central plant that employs water-to-water heat pumps to upgrade recaptured heat from the ice plant. The low temperature hot water will be used to supply under slab heating, snow melt pit, domestic hot water preheating, pool heating, ventilation air heating and space heating. Two condensing boilers supplement the heating energy, and provide high temperature hot water for DHW and the hot pool. The heat pumps will also provide chilled water to the air-handling unit cooling coils and pool air handling unit dehumidification coils. Additional dehumidification will be provided in the ice arena by desiccant gas-fired units. The building's heating will primarily be met by the air systems (17 air handling units in all) with additional zone reheat coils providing zone temperature control. Opportunities for heat recovery from exhaust air of the natatorium, change rooms, and various community centre spaces have been investigated.

Supplementing the hot water system described above, additional hot water will be available from an active solar hot water system. This thermal energy will be utilized to heat the outdoor pool in the summer months and preheat the DHW system in the winter months (when the outdoor pool is not in operation).

OVERALL MODELING STATEGY

The design assistance goals of this project required a unique building simulation strategy balancing the capabilities and weaknesses of available building simulation tools. The building envelope and load analysis was well suited for the DOE 2.2-based simulation tool eQUEST (2006), while the simulation group felt a separate simulation tool was required for the complex heat recovery and systems questions. For this, a supplemental model was developed using TRNSYS (Klein et. al., 2004) to specifically provide accurate predictions of the building's mechanical systems operation. Additional modeling input for renewable energy applications was gained using the online project analysis tool RETScreen (2006).

The eQUEST simulation software provides hourly analysis of thermal and electrical building loads considering the effects of external conditions (solar, temperature, and wind effects) and internal conditions (occupancy, lighting, scheduling, equipment and water usage). For this reason, eQUEST was employed to determine the heating, cooling, ventilation, lighting, and electrical loads of the community and aquatic centres. By developing a baseline version of the building as specified by ASHRAE 90.1-2001 requirements for building energy standards, this tool could be used to determine the energy savings potential of varying conservation measures.

Loads from building space conditioning have typically been simulated with hourly timesteps since weather files have this resolution and most space conditioning applications can be simulated with a reasonable level of accuracy with this approach. As well, system and loads interaction are not simulated with a high degree of accuracy by most programs. However, for situations where all loads are satisfied, this limitation does not typically pose a problem.

In the current project, most anticipated loads were for space conditioning, so an hourly timestep without system interaction capability was deemed appropriate. As well, information about waste heat available from the ice plant refrigeration system was quite cursory. Seasonal average values were supplied by the refrigeration consultant, along with anecdotal information about typical system operating behaviour and the sequence of satisfying rink-related loads. Therefore, an hourly timestep simulation without system interaction was also deemed appropriate.

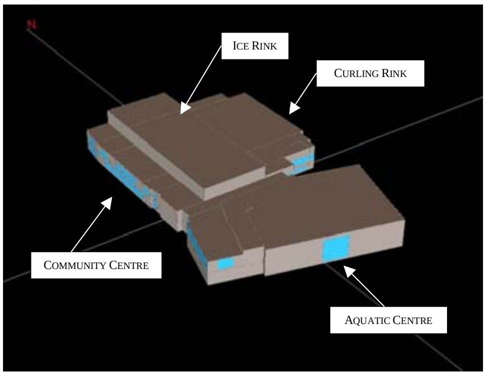

Figure 1 eQUEST Rendering of Community and Aquatic Centres

eQUEST is well suited for building envelope and loads modeling; however, the program is limited in simulating process loads (such as the pools and ice plant) and is even more limited in simulating complex, highly integrated mechanical systems. A TRNSYS model was therefore developed and employed to provide guidance on system sizing to adequately balance the capacities and sequencing of the community centres' complex hot and cold water loads. Hourly hot and chilled water demands derived from the eQUEST model as well as the load predictions for the pools, showers, and miscellaneous rink-side hot water loads were required as inputs. The TRNSYS model was then employed to better understand the capacities and demand schedules required to balance the building's loads with available recovered heat from the ice plant, solar systems, heat recovery, and supplemental mechanical systems.

Essentially, the building loads and plant systems have been decoupled with the two simulation tools, employing post-processing techniques to ensure compatability between the hourly results from eQUEST translated into load inputs to the TRNSYS model.

LOADS ANALYSIS

In order to accurately predict the operation and energy consumption of the community and aquatic centre, a detailed understanding of the building loads is first required. The heating loads associated with the rinks and pools are anticipated to be large and will therefore greatly influence the systems operation. Accurate predictions of loads and scheduling are essential to the accuracy of the building simulations. Detailed predictions were established through consultation with design engineers, pool experts, rink experts, and, most importantly, regional parks board engineers with previous systems and building load data and experiences.

Overall Building Heating Load

As mentioned previously, the eQUEST model was developed in order to predict the amount of hot water required to meet the entire building's heating load for each hour of the simulated year. The resulting hourly loads are used as input into the TRNSYS model to analyze the balance of hourly demands with available heat recovery. Typical internal heat gains are anticipated from occupants, lighting, and equipment. Additional process level gains to represent the rinks and pools were also calculated (ASHRAE, 2006) and included in the building energy model. The convective sensible heating load of the ice sheets was determined to be 51.3 W/m^2 for the curling rink and 67.5 W/m^2 for the ice arena. A load of 50.1 W/m^2 was implemented to represent the latent cooling loads of the pools in the aquatic centre (sensible load was assumed to be negligable as pool water and natatorium air temperatures are similar).

Poolside Heating Loads

Predicting the energy consumption of pool facilities is a difficult task due to the variance of anticipated occupancy and activity levels. For this reason, load predictions were established by combining prediction models based on industry research with anticipated schedules and past operational experience obtained by close consultation with the design team and the regional parks board.

Pool Heating Loads: It was determined that the evaporative losses were by far the most significant portion of the heating loads of the three indoor pools (far exceeding radiation, convection and conduction losses). A prediction method developed by Shah (2004) was used to predict the evaporative losses based on pool surface area, water and air properties, ratio of occupied to unoccupied periods, and a derived pool activity factor. It is anticipated that 1000 people would use the aquatic centre each day. This load was dispersed evenly over the operable hours (6am to 9pm) to determine the number of pool occupants at any time.

Pool Filling Loads: The calculations to determine the loads associated with refilling of the indoor pools depended on the frequency and fill time anticipated by the parks board. The main lap pool is expected to be emptied and filled once a year with a maximum refilling period of 72 hours. This results in a large hot water load occurring once a year (early September) where 320 kW are required for the entire 72-hour period. The leisure pool (also emptied and refilled once a year over a 72 hour period) would require a 162 kW hot water load. Finally, the whirlpool will be emptied and refilled once a week over a maximum period of 4 hours. This would result in an hourly hot water load of 217 kW.

Pool Shower Loads: The calculations to determine the pool shower loads were based on the same occupancy as the pool loads. It was anticipated through consultation with the facilities operators that every patron would shower for 5 minutes using 0.16 L/s of hot water. This load was dispersed evenly over the natatorium's operable hours resulting in an hourly heating load of 171 kW.

Outdoor Pool Loads: The outdoor pool load is difficult to determine since the local wind speed over the pool greatly influences evaporation, and subsequently the heating load. A rough estimation of the heating load was obtained from RETScreen for the pool area specified. Note that no nighttime cover was specified in the design (as anticipated by the parks board). The outdoor pool load was estimated at 185 kW plus an additional hourly DHW load of 73 kW due to showers. The outdoor pool heating load was averaged over the entire day.

Rinkside Heating Loads

The second set of hot water loads required for the systems load modeling originate from the use and maintenance of the two ice sheets. These include hot water loads to fill the ice resurfacer and snow melt pits, provide heating to the under-rink piping network, as well as provide hot showers for the arena patrons.

Ice Resurfacer Fill Loads: The ice resurfacer requires hot water to resurface the ice. Each resurfacing requires 600L of hot water at approximately 60°C. The parks board anticipates theat the ice resurfacer will run 12 times per day when the rinks are operating. The result is an hourly load of 40 kW.

Under Rink Heating Loads: Low temperature under-slab heating is required beneath the ice surfaces in order to prevent frost heave. Based on the previous experience of the parks board and the refrigeration consultant, this heating load was anticipated to be 4% of the gross refrigeration load. This results in a constant heating load of approximately 52 kW when the rinks are operational.

Snow Melt Pit Loads: After each time the ice resurfacer cleans the rinks, the resulting ice shavings are deposited into the snow melt pit and require hot water to be melted. It is known that this process requires approximately 600 L of low grade hot water to melt the shavings in a maximum duration of 45 minutes. The resulting heat load is 68 kW.

Rink Shower Loads: The rink-side shower loads were calculated in a similar manner as the poolside shower loads. It was anticipated that every hockey player (20 per game) would shower for 4 minutes using 0.16 L/s of hot water after each game (four per day). This load was considered to occur in the early morning and late evening hours of operation, resulting in an hourly heating load of 41 kW.

Ice Plant Electrical Load: It is difficult to predict the anticipated annual electrical load of the ice plant as operation of the three compressors varies depending on the cooling load. In order to approximate this load a rough estimation was developed. Consultation with the refrigeration consultant revealed that the first compressor (25 kW) was anticipated to run full time to maintain the two ice surfaces (24 hr/day), the second compressor (25 kW) would operate each time that the ice was resurfaced (approx. 6 hr/day), and the third compressor (25 kW) would be operated only during the ice making process (approx. 72 hr/year). Based on these approximations, the electrical load for the ice plant was determined to be roughly 10,000 GJ/yr.

SYSTEMS ANALYSIS

The significant mechanical system aspects that were modeled included:

- Six heat pumps to provide chilled water for cooling and dehumidification. These heat pumps also use ice plant waste heat and add it to the pools and DHW preheat,
- A chilled water loop, hot water loop, and a heat recovery loop from the ice plant,
- The ice plant and thermal storage tank for low quality waste heat,
- Boilers and domestic hot water preheat/storage tanks, and
- A solar hot water system.

Figure 2 illustrates the general arrangement and integration of the mechanical systems.

***Heat Pumps*:** The heat pump plant contains six water-to-water heat pumps. This plant has a number of operational objectives. The first is to cool the chilled water loop. Depending on the chilled water load, the required number of heat pumps will connect to the chilled water loop to provide water at 7ºC. The heat drawn from the chilled water loop is pumped to the hot water loop to be used in the building. If the chilled water loop does not require all of the heat pumps to be operating, the remaining heat pumps will connect (through a 3 way valve) to the ice plant thermal storage tank. If the tank is of sufficient temperature these heat pumps will draw thermal energy from the tank, and inject it into the hot water loop.

***Chilled water loop*:** The chilled water loop services the AHUs throughout the building, and is also used for natatorium dehumidification. It is a variable flow loop that requires 7ºC water and has an approximate return temperature of 12ºC.

***Hot Water Loop*:** The hot water loop distributes heat to the building and to the pools. This is a variable flow loop with a setpoint of 46ºC, and an approximate return temperature of 43ºC. During pool fill operation, the loop setpoint can be increased to 57ºC to ensure pool warm up in adequate time. The hot water loop gets its energy primarily from the heat pump plant. If the heating load exceeds what the heat pump plant can deliver, two condensing boilers will add heat into the loop.

***Ice Plant*:** The ice plant system was designed outside of the scope of this study. The design included the necessary ice plant heat recovery provisions provided by the refrigeration consultant. Internal to the ice plant design were heat recovery provisions that created hot water for the ice resurfacer, the ice melt pit, and under slab heating for the ice surfaces. The remaining heat was available for building use via a water loop that had a maximum temperature of 24ºC. Due to the internal workings of the ice plant, the return water temperature to the plant was not permitted to be below 18ºC. A tempering valve was present to maintain this minimum return water temperature.

***Thermal Storage*:** A thermal storage tank was proposed to act as a buffer between the heat pump plant and the ice plant in order to smooth out differences between the periods when the ice plant is rejecting heat, and when the recovered heat can be used in the building.

***Boilers and Domestic Hot Water*:** The initial design contains domestic hot water pre-heat tanks. These tanks draw energy out of the hot water loop via a heat exchanger. The preheat tank for the pool DHW is connected to a second heat exchanger that can draw heat out of the solar thermal system. The water flows out of the preheat tank into a storage tank where the water is heated to 60ºC by non-condensing gas fired boilers.

***Solar Thermal System*:** In the initial design, a solar thermal system is connected to both the outdoor pool, and the domestic hot water pre-heat tank. If the outdoor pool is not operational, or does not require heat, the remaining solar thermal energy can be added into the pre-heat tank. If the pre-heat tank exceeds 60ºC, excess energy can enter the hot water loop through the appropriate heat exchanger. The solar thermal system included with this analysis is a 45 m^2 array of glazed flat plate collectors.

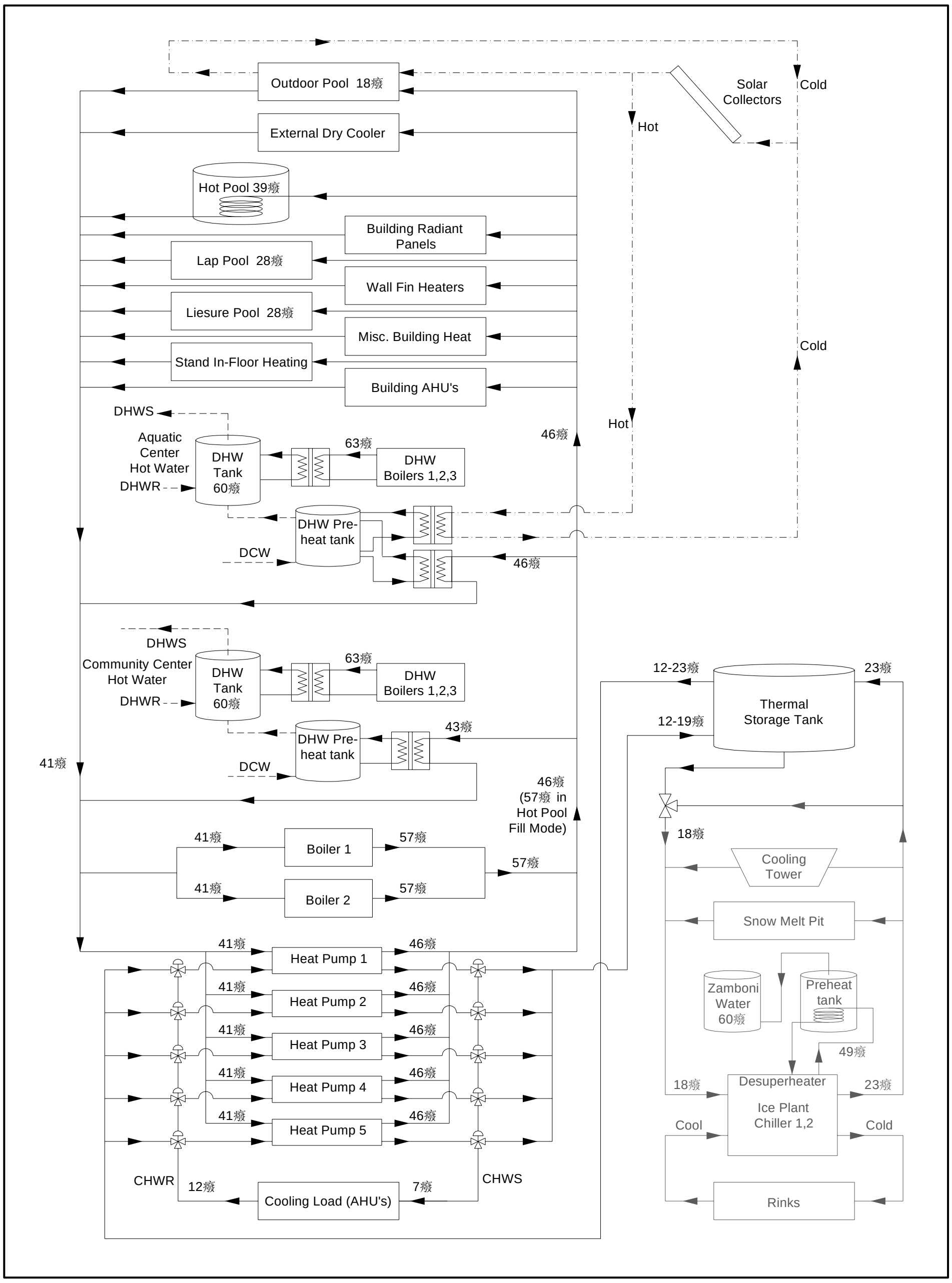

Figure 2: Schmatic Design of Mechanical Systems

RESULTS & ANALYSIS

The interconnected building simulations provided essential design guidance that was not previously accessible to the design team. Some of these issues have been presented in this section.

First, the eQUEST model was able to assess energy conservation measures as outlined previously. The most significant building energy conservation measures are the building envelope upgrade, and incorporating some form of heat recovery on the natatorium exhaust stream. These measures are recommended for implementation and will reduce the cost of building operation dramatically. Installing CO_2 (occupancy) sensors creates notable energy savings for very little cost. Installing energy efficient lighting and control systems, and placing ventilation heat recovery in the change rooms and curling lounge provide modest, but still attractive energy and cost benefits.

Secondly, the TRNSYS model utilized building load predictions to determine systems energy savings. It was found that replacing the reverse flow exhaust heat recovery device with a counter flow heat exchanger and a cooling coil integrated with the buildings chilled water system will allow the heat pump plant to satisfy the building and pool heating load for approximately 8 months of the year. A large energy cost savings is predicted, as well as a large reduction in energy consumption and green house gas emissions. The hot water loop is of sufficient temperature for condensing boilers to be effective. In all situations these boilers will provide at least 25% of the buildings heating energy. Thus, significant energy savings will occur if condensing boilers are used. It was also observed that the size of the ice plant heat recovery thermal storage tank does not greatly influence the amount of energy recovery from the ice plant. In order to achieve a 7% increase in heat utilization from the ice plant, the tank size must be increased from 1 to 20 m^3. A tank size of approximately 5 m^3 is recommended to act as a thermal buffer between the ice plant and the heat pump plant.

As modeling results began influencing the progression of system design, two unique heat recovery strategies for the natatorium emerged. The original strategy called for a high efficiency reverse-flow unit (natatorium heat recovery strategy 1). Factors such as climate, dehumidification requirements, and heat exchanger design suggested that a cost savings could be achieved with a cross-flow heat recovery device with a cooling coil in the exhaust stream (natatorium heat recovery strategy 2). The building performance varied significantly for each scenario and therefore the results are presented for each path.

Natatorium Heat Recovery Strategy 1 Findings:

- The heat pump plant is underutilized. An additional heat source for the plant should be considered.
- Summertime ice plant operation will reduce the cost of heating the pools significantly, partially subsidizing the cost of running the ice plant over the season. Even with summertime ice plant operation, the daily heat demand for the building and pools cannot be met with the heat pump plant.
- The domestic hot water preheat tanks are not necessary. If removed, condensing boilers would be effective.
- A large solar system would be effective due to the large thermal load required over the entire year, partially created by the outdoor pool operation. The solar hot water system should primarily heat the pools to maximize collection efficiency.

Natatorium Heat Recovery Strategy 2 Findings:

- The heat pump plant has sufficient energy sources to satisfy the building heating and pool loads from April through to the end of October.
- Summertime ice plant operation will not produce a heating energy cost benefit.
- The domestic hot water preheat tanks can be fully utilized with recovered heat for seven months of the year. The full benefit of condensing boilers on the domestic hot water system will not be achieved due to significant preheating of the domestic hot water. Condensing boilers are not recommended for the domestic hot water system.

Since the heat pump plant satisfies the thermal load during the seven warmest months, the payback for a solar thermal system becomes less attractive. A large solar thermal system would mainly displace heat pump operation, and would not be economical. A smaller solar thermal system can still be beneficial since it can mainly displace the natural gas required to heat the higher temperature domestic hot water. In order to maximize energy cost savings, the solar system should primarily be connected to the domestic hot water preheat tanks.

CONCLUSIONS

This paper attempts to shed light on the importance of building simulation's unique and essential role in design development for projects with complex and transient load predictions, system analysis, and the balancing of the two via process energy recovery techniques.

Important design considerations were brought to light with the building and systems simulations. These include:

- Heat pump system sizing,
- Thermal storage requirements to balance heat recovery and loads,
- Potential for envelope and lighting upgrades,
- Boiler selection, and
- Effective heat recovery configurations.

The building simulations proved to be an essential tool to the design team for providing sizing and control information that were previously unknown due to the complex system and variable loads. This contributed significantly to the design process by reducing system oversizing and redundancy.

As well as technical design contributions, important experience was also gained through the integrated design process. Key areas of focus to ensure a successful relationship between simulation specialists and the design team were determined to be:

- Acceptance by all stakeholders to include building simulation in early stages of design process,
- Inclusion of all stakeholders (from design team to building operators, to future occupants) to accurately determine the building and facility usage patterns and thus predicted loads,
- Understanding of multiple simulation tools by simulation specialists to provide solutions adaptable to unique design considerations,
- Creating robust, yet flexible, building models that can provide useful feedback to the design team at a rate comparable with the rapidly evolving design process.

REFERENCES

ASHRAE, 2006. 2006 ASHRAE Handbook – Refrigeration. Atlanta: American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc.

eQUEST, 2006. Version 3.6, www.doe2.com/equest

Klein, S.A., W.A. Beckman, J.W. Mitchell, J.A. Duffie, N.A. Duffie, T.L. Freeman, J.C. Mitchell, J.E. Braun, B.L. Evans, J.P. Kummer, R.E. Urban, A. Fiskel, J.W. Thornton, N.J. Blair, P.M. Williams, D.E. Bradley, T.P. McDowell, M. Kummert. 2004. TRNSYS 16 – A TraNsient System Simulation program, User manual. Solar Energy Laboratory. Madison: University of Wisonsin-Madison.

RETScreen. 2006. RETScreen International Clean Energy Project Analysis Software. United Nations Environmental Programme & Minister of Natural Resources Canada, Version 4.

Shah, M.M. 2004. Calculating Evaporation from Indoor Water Pools, HPAC Engineering, p.21-26, March.