COMPARISON OF DIFFERENT MECHANICAL SYSTEMS MODELS FOR A PASSIVE SOLAR GREENHOUSE WITH TWO THERMAL ZONES

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ABSTRACT

The construction of passive solar greenhouses on urban rooftop is gaining popularity in Canada. This type of greenhouse provides many energetic and economic advantages. However, their conception remains atypical. Heating and ventilation systems generally recommended for standard greenhouses are often inadequate for this kind of specific application. The objective of this article is to evaluate different mechanical system types and configurations to be installed in a passive solar greenhouse with two thermal zones. Three systems, forced air with terminal reheats, baseboards, and radiant floor, will be modeled using the OpenStudio/EnergyPlus software. The results will be presented for each option and recommendations will be provided based on the analysis of thermal comfort and energy use.

INTRODUCTION

The design of a greenhouse for yearly agricultural harvesting in a northern climate, where temperatures vary between 30°C and -30°C, is a significant challenge. Different types of passive solar greenhouses suited for northern climate have been developed and studied in the 70s (Lawand 1974). However, the enthusiasm was not strong enough to give rise to major changes in the industry. Design methods proposed by ASHRAE (2007) and ASAE (2003) are mainly elaborated for standard commercial greenhouses located in moderate climates. The proposed standard greenhouse model is very energy intensive, and this is even truer for northern climate. Consequently, several researchers have studied energy saving measures and systems to minimize the energy use of greenhouses (Albright 1980, Albright, Langhans et al. 1981, Willits 2003, Dayan, Dayan et al. 2004, Piscia, Muñoz et al. 2015). The results obtained in these studies once again are based on the standard greenhouse model. Nevertheless, some studies did combine complex CFD analysis and energy simulations to obtain their results (Piscia, Muñoz et al. 2015). The proposed methodology by Piscia, Muñoz et al. (2015) could be used as the basis for the design of less conventional greenhouses; however, the models and calculations would have to be adapted to the case under study.

This study aims to evaluate the indoor air conditions in a passive solar greenhouse with two thermal zones using energy simulation, in this case OpenStudio which acts as an interface for EnergyPlus. The modeling of the greenhouse in energy simulation software enables detailed analysis of the influential parameters such as the insulation thickness, orientation, the percentage of fenestration, etc. It can also estimate the impact of various passive measures such as thermal and solar curtains or increased thermal mass on the energy use and indoor conditions.

This study focuses on the modeling of the greenhouse envelope, the design and comparison of different heating, ventilation and air conditioning (HVAC) systems and the indoor conditions inside the greenhouse. The objective is to determine which system provides the most suitable solution when thermal comfort and energy use are used as design decision criteria.

Thus, this paper presents and compares the modeling and design of three types of HVAC systems for a solar passive greenhouse. All the systems are completed with a VAV air distribution system. Three different heating systems are compared: (1) an air-forced heating system with terminal reheats, (2) an electric baseboards heating system, and (3) an electric radiant floor heating system.

CASE STUDY

Although several studies could have been conducted to evaluate the impact of various architectural parameters of a passive solar greenhouse, the objective of this study was to study the different scenarios for the HVAC systems and their effects on the indoor conditions and energy use. Thus, the geometric model of a greenhouse currently being designed at École de techonologie supértieure (ÉTS), located in Montreal, was selected to complete the study.

Description of the building

The modeling of the building was performed using SketchUp and the OpenStudio plug-in for EnergyPlus as presented in Figure 1.

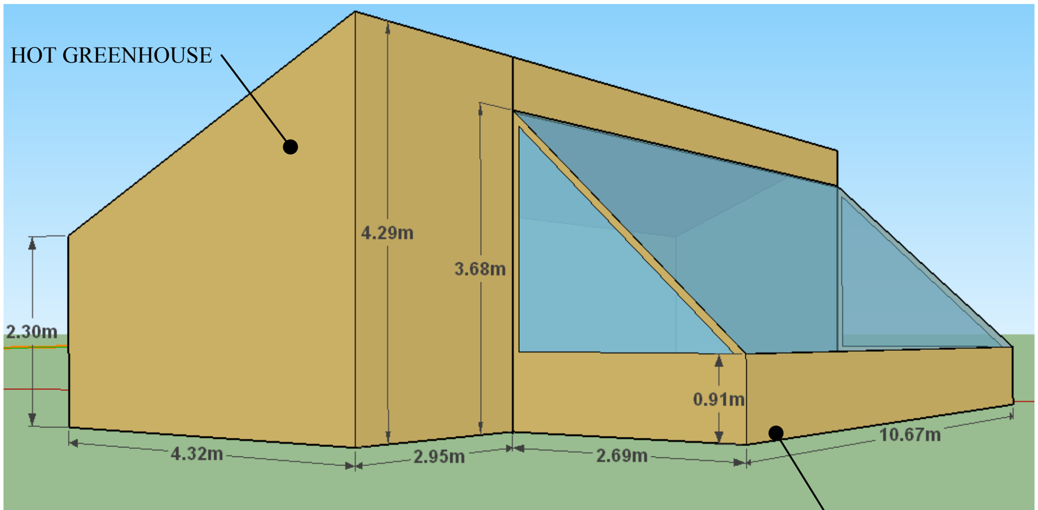

Figure 1
SketchUp model of the building

Table 1
Indoor conditions of the greenhouses

PARAMETERS	COLD GREENHOUSE		HOT GREENHOUSE
	SUMMER	WINTER	
Minimum night temperature, ºC	13	4 à 10	18
Min/Max daytime temperature, ºC	13/30	13/20	23/30
Min/Max humidity, %	45/70	45/70	45/70

The building (excluding the part occupied by the mechanical room) is divided into two thermal zones named cold greenhouse and hot greenhouse. The design is for roof installation on one of the ÉTS building. The cold and hot greenhouses design conditions to be considered are presented in Table 1.

A plan view of the building and thermal zones arrangement is shown in Figure 2.

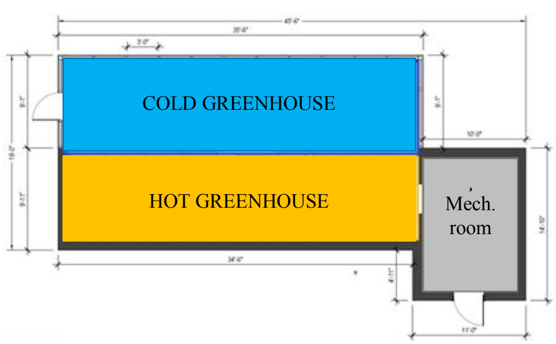

Figure 2
Plan view of the thermal zones

The cold greenhouse, which has the glazed façade, faces south at an angle of 65º. The cold and hot zones of the building have a floor area and volume of 28.7 m²/112.8 m^3 and 32.1 m²/112.8 m³, respectively. All the exterior walls have the same thermal characteristics. They are formed of Structural Insulated Panels (SIP) consisting of an insulating core of polyisocyanurate sandwiched between two Magnesium Oxide (MgO) panels. The MgO and insulation panels are 1.27 cm and 15.24 cm thick, respectively. The outdoor glazing and the glazing installed on the inner surface between the two greenhouse thermal zones are acrylic double glazed panels having a thickness of 16 mm. The tilt angle of the south window is 45º relative to the horizontal. The roof tilt angle is 24º to the horizontal. The total height of the greenhouse, at the junction of the cold and hot greenhouses is 4.29 m. The floor consists of a 10.1 cm concrete slab.

The occupants internal gains within the building are modeled considering two occupants per greenhouse doing work standing up (170 W/person) from 8:00 to 17:00, Monday to Friday, as defined in ASHRAE Standard 55-2010 (ASHRAE 2010). The lighting density is 60 W/m² of floor area occupied by plants. The floor areas occupied by plants of the cold and hot greenhouses are 17.74 m² and 11.06 m², respectively. Table 2 shows the lighting schedules for each month of the year.

The infiltration rate of the cold greenhouse is estimated at 0.6 air changes per hour (ACH) as per ASAE (2003) recommendations for new construction. For the hot greenhouse, since its envelope mainly consists of insulating panels, the infiltration rate is estimated at a lower value of 0.3 ACH.

Table 2
Lighting schedules

MONTH	ON TIME	OFF TIME
January	18h00	2h00
February	18h00	2h00
March	19h00	1h00
April	20h00	1h00
May	20h00	00h00
June	21h00	23h00
July	21h00	23h00
August	20h00	00h00
September	19h00	1h00
October	18h00	1h00
November	18h00	1h00
December	17h00	3h00

Like humans, plants breathe and perspire. In the winter, in order to reduce the heating requirements, the amount of outside air is minimized. Maintaining adequate airflow is essential to ensure optimal harvesting of the crops. Improper ventilation rate can have a negative impact on productivity and plant health. The plant characteristics, such as their consumption of oxygen and CO_2, and thermal load contribution (sensible and latent), vary greatly depending on the type, maturity and health of the plants. (ASAE 2003). Little information is available in terms of reference values to be taken into account to model the plant contributions to the internal loads. Consequently, the plants were not modeled in this study. However, the required minimum fresh air was estimated at 10 L/s/m² as per ASHRAE (2007).

Load calculations

A first simulation of the building was completed without any mechanical equipment (ideal load on) to determine the cooling and heating requirements of both greenhouses. To ensure the validity of these results, the obtained values were compared with the calculation method proposed by ASAE (2003). The heating load of each of the greenhouse is approximated using equation (1).

$$q = q_{vent} + q_i + q_{rc} \quad (1)$$

Where q_{vent} represents the outdoor air ventilation heat losses in W, q_i the heat losses due to infiltration in W and q_{rc} the radiation, conduction and convection heat losses in W. The outdoor air ventilation heat losses (q_{vent}) are estimated by equation (2), while q_i and q_{rc} are estimated by equations (3) and (4), respectively.

$$q_{vent} = Q \cdot \rho \cdot c_p \cdot (t_i - t_o) \quad (2)$$

Where Q is the outdoor air flowrate (minimum fresh air level) in m³/s, ρ is the outdoor air density in kg/m³, c_p is the outdoor air specific heat in J/kg°C, t_i is the greenhouse indoor air temperature in °C, and t_o is the outdoor air temperature in °C.

$$q_i = \rho_i \cdot N \cdot V\left[c_{p_i}(t_i - t_o) + h_{fg}(W_i - W_o)\right] \quad (3)$$

Where ρ_i is the indoor air density in kg/m³, N is the infiltration rate in s^{-1}, V the zone volume in m³, c_{pi} is the indoor air specific heat in J/kg°C, h_{fg} is the enthalpy (latent energy) of water vaporisation at t_i in J/kg, W_i is the indoor air specific humidity in kg_{water}/kg_{air}, and W_o is the outdoor air specific heat in kg_{water}/kg_{air}.

$$q_{rc} = U \cdot A_c(t_i - t_o) \quad (4)$$

Where U is the overall heat transfer coefficient in W/m²·°C and A_c is the surface area of the building envelope in m². For the exterior walls, the U-value is 0.1517 W/m²·°C, while the windows have an estimated U-value of 1.8457 W/m²·°C. These values take into account the thermal resistance of the materials as well as the radiation and convection surface resistance (ASHRAE 2005). For the window installed between the two thermal zones of the greenhouse, the temperature difference is calculated using the two greenhouses indoor air temperature set points as presented in Table 1. Table 3 presents a comparison of the simulated and calculated heating load values. For the hot and cold greenhouses, the discrepancies are below 1%.

Table 3
Heating loads

	HOT GREENHOUSE	COLD GREENHOUSE
Simulated, W	22,900	18,593
Calculated, W	22,987	18,544
Relative difference, %	0.4	0.3

Cooling loads are more dynamic than the heating loads and their estimation requires a more detailed analysis. To assist the analysis process of the heat balance equations used to determine the cooling load, the use of energy simulation software, such as EnergyPlus, is recommended (ASHRAE 2005). Table 4 presents the estimated cooling loads for the modeled greenhouses. The simulated cooling loads are lower than the heating loads. This is expected since the heating season in the Montreal area is two to three times longer than the cooling season.

Table 4
Estimated cooling loads

	HOT GREENHOUSE	COLD GREENHOUSE
Simulated, W	4,473	9,821

DESCRIPTION OF THE HVAC SYSTEMS

An iterative process was followed for the system sizing of the different options to minimize the energy use while simultaneously maintaining the required indoor air conditions. Typically, systems are modeled such that they comply with the temperature set points, moisture and fresh air requirements. However, in this study, the additional moisture generated by the plants was not modeled; however, this could influence the obtained results as plants play a major role in the supply of moisture to the space (Piscia, Muñoz et al. 2015). For this reason, the proposed systems are selected to meet the temperature set point and fresh air requirements rather than the greenhouses required humidity level.

The selected air distribution system is a variable air volume (VAV) system complete with a pre-heat electric coil and different zone heating options. Normally, no mechanical systems are provided in passive greenhouses. Thus, the proposed HVAC systems have been modeled without any air-conditioning equipment to study the potential of using only outdoor air to maintain the indoor air conditions during the cooling season. The objective was to determine whether it was realistic to cool the greenhouses using only outdoor air or if overheating would occur often.

The required system airflow rate is determined by the amount of outdoor air required to maintain indoor air conditions during the cooling season without the use of air conditioning equipment. The outdoor air temperature used to determine the maximum fan airflow rate is taken from ASHRAE (2005) weather data for Montreal and is equivalent to the 1% dry bulb temperature. This criterion was selected in order to enable the cooling of the greenhouse with only outdoor air, since the 0.4% temperature of 30°C is equal to the maximum allowable temperature within the greenhouses as specified in Table 1. Even if this aspect is taken into account, it is expected that the temperature within the greenhouses will rise above the maximum allowable temperature. However, the results will allow an estimation of the maximum temperature reached and its duration under the proposed outdoor air cooling scheme.

Mechanical shadings were also modeled to minimize the loads and evaluate the potential of this energy saving measure for the proposed building. The shading controls the sun intensity using the OnIfHighSolarIntensity object. This measure is implemented for the cooling season only, from May to August. The shading material was modeled with a solar transmission factor of 30%.

Electrical terminal reheat

The first heating system being modeled is a VAV system with an electric pre-heating coil with terminal reheats in the hot greenhouse.

During the heating season, the room temperature is controlled using a thermostat (setpoint manager) for the terminal reheats (single zone reheat temp). The supply air temperature varies between 10°C and 30°C and is determined according to the heat losses of the cold greenhouse. The set point temperature in the hot greenhouse is maintained by the reheat terminals that warm the supply air to a maximum temperature of 35°C. Without the reheat terminals, the temperature of the hot greenhouse is below the heating set point for more than 6000 hours.

To reduce the energy use of the pre-heat coil, the system was also modeled with a differential dry bulb economizer. The operation schedule of the economizer was adjusted such that the system runs with a 100% outdoor air to cool the greenhouses whenever required.

Electric baseboards

This system is relatively similar to the previous system. The main difference is the maximum supply air set point that is adjusted to the cold greenhouse temperature set point of 13°C. Thus, the thermal losses by infiltration and conduction (and conditioning of the fresh air for the hot greenhouse) are overcome by the heating devices installed within the zones, which in this case are wall mounted electrical baseboards.

Radiant floor

For this system, the air distribution is the same as previously described. However, the zone heating, used to overcome the infiltration and conduction losses, is done using an electric radiant floor. Floor heating is considered as a good practice when plants container can be set directly on the floor (ASAE 2003). It is also well suited for plants that need minimum protection, like the ones that can grow in the harder winter conditions of the cold greenhouse.

This system has advantages and disadvantages that influence both the energy use and indoor air conditions. The time lag of a radiant heating floor, either hot water or electric, is longer than other heating system types. Indeed, in the winter, when heat losses increase at night, the thermal capacitance of the floor will allow lower energy use to maintain the indoor air conditions.

However, after night setback, in the morning when the set point increases rapidly, there is a time delay for the system to be able to reach the desired conditions even when the installed power is high. Consequently, the heating schedule was modified to include a gradual temperature set point increased. As an example, Figure 3 presents the proposed temperature set point control scheme implemented in the model for the cold greenhouse. Similar adjustments were also made to the temperature set point schedule of the hot greenhouse.

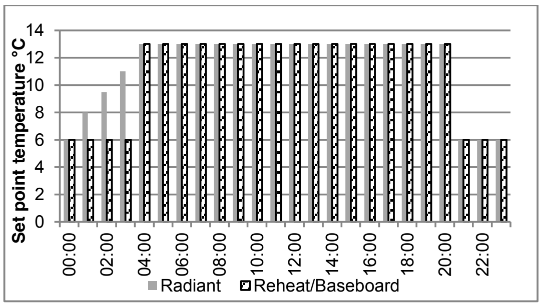

Figure 3
Temperature set point of the cold greenhouse

RESULTS AND DISCUSSION

The obtained results for all heating options are analyzed and discussed using various criteria as presented in the following sections.

Zone conditions

Before completing the energy use comparison, the first thing that was verified was if the proposed systems met the required design conditions. This is influenced by the system type and design. One of the many options available in OpenStudio is automatic sizing of the HVAC equipment, which attributes default values to many of the design parameters. The default values can also be modified based on the selected equipment capacity or available manufacturer information.

In this study, both approaches were used sequentially. First, the fan was dimensioned using automatic sizing under the proposed cooling scheme, i.e. no refrigeration equipment was specified. The obtained results were then used to validate the calculated capacity of the pre-heat coil and terminal reheats. Then, the modeled capacities were decreased to reduce the maximum power. This led to a few hours were the temperature set point of the greenhouses were not met, but improved the energy efficiency of the system. The majority of the time, HVAC systems operate at part-load conditions; consequently, selecting equipment having a lower capacity could lead to increase efficiency for most of the operating hours. Furthermore, the initial cost can also be decreased under the proposed equipment selection approach. For electric heating, the equipment oversizing does not affect the efficiency at part-load conditions; however, since the system comparison could be performed for other heating systems (gas or hot water), this design criterion was still taken into consideration.

For the baseboards and radiant floor, there are still some limitations under the automatic sizing option available in OpenStudio. Therefore, the required power output was determined iteratively. Table 5 presents the installed heating capacities for each of the systems, while Table 6 presents the zone conditions unmet hours for each of the system.

Table 5
Heating capacity of the installed equipment

	COLD GREENHOUSE	HOT GREENHOUSE
Pre-heat coil capacity, W	50000	50000
Reheat coil capacity, W	0	8000
Baseboards capacity, W	10000	10000
Radiant floor capacity, W	12000	10000

Table 6
Number of unmet hours

SYSTEM	COLD GREENHOUSE		HOT GREENHOUSE	
	Heating	Cooling	Heating	Cooling
Terminal reheats	11	47	57	41
Baseboards	11	44	52	39
Radiant floor	8	55	46	47

In the cold greenhouse, since the set point is already low (4 to 10ºC as per Table 1), particular attention was given to the number of unmet hours since it could lead to serious consequences such as freezing, death of plants, etc. In the hot greenhouse, the maximum number of hours where the heating set point is unmet equals to 57 hours, which is equivalent to 0.7% of the time over a whole year. This percentage is relatively low and tolerable if one refers to the design standards of ASHRAE (2005). For the cooling, the percentage of unmet hours on a yearly basis is maximum 0.6%. For both cases, the set point dead band is set to 0.2ºC, which is relatively low. By changing the dead band value, the number of hours when the set point is not reached could be reduced (Parker 2015). Without modifying this parameter, it is interesting to observe the temperature and airflow fluctuations within the zones. As an example, Figure 4 presents the system operating conditions for the cold greenhouse during unmet hours.

Figure 4 shows that the temperature of the cold greenhouse is never above 33.2 ºC during the cooling season. This temperature is below the maximum tolerable temperature of 35 ºC for the plants (Ponce Cruz 2015). It is important to emphasize that this analysis does not take into account the contribution (or withdrawal) of energy by the plants or their thermal mass. Consequently, a more detail analysis that includes the impact of the plants on the heat balance of the greenhouses is recommended before deciding if additional cooling equipment would be required.

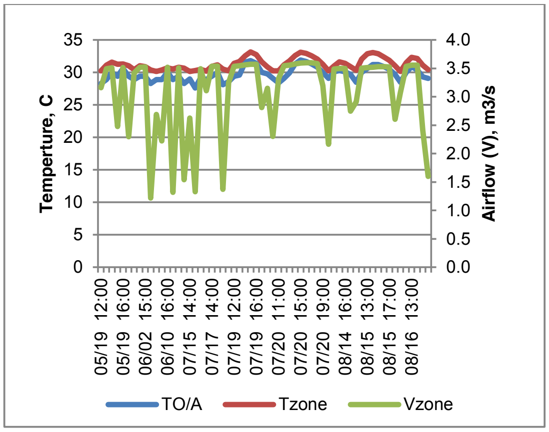

Figure 4
Cold greenhouse operating conditions when the indoor air conditions are not met

Energy use

One important aspect when comparing the different scenarios is the energy use. Table 7 and Figure 5 present the annual and monthly energy use for the three different heating systems.

Table 7
Annual energy use for the three heating options

SYSTEM	ANNUAL ENERGY USE, KWH	RELATIVE DIFFERENCE, %
Reheat	99,712	
Baseboard	99,713	-
Radiant floor	90,408	-9.3

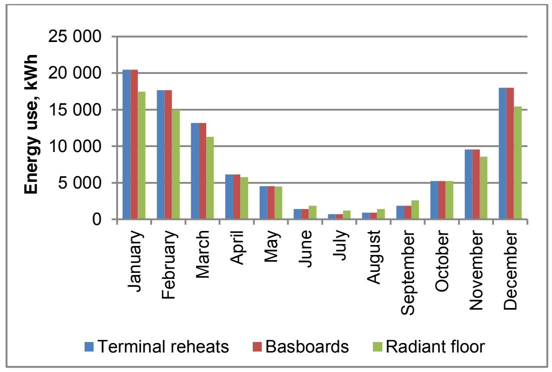

Figure 5
Monthly energy use

Figure 5 shows that during the summer months, the cooling requirement of the cold greenhouse causes a heating demand for the hot greenhouse. Also, since the heating set point in the cold house is much lower than for the hot greenhouse, this can also cause a heating demand in the hot greenhouse. This occurs, for example, when the supply temperature set point of the cold greenhouse is 15ºC, explaining as well the heating occurring during the summer months. Overall, on a monthly basis, the energy use is quite similar from one system to another. This is to be expected since these are all electric heating systems having an efficiency of a 100%. The energy use variations between the systems are caused mainly by airflow and supply air temperature differences. Also, the energy use of the radiant floor system is slightly lower than for the other two systems probably caused by the thermal mass of the floor. The radiant floor system also has the advantage of reducing the peak power demand. In terms of unmet hours, it also has the least amount of unmet hours during the heating season (Table 6). However, the thermal mass of the floor seems to increase the number of unmet hours during the summer months compared to the other two systems.

CONCLUSION AND FUTURE WORK

The findings of this study should serve as a starting point for the completion of more detailed analysis. The comparaison of the analytical solutions and the simulation results showed the potential of using OpenStudio to complete more detailed analysis for the design of passive greenhouses. The results also showed that the energy use could be reduced by the use of a radiant floor heating systems. However, several aspects were left out of the study due to time constraint. The first aspect to be considered would be to complete an economic analysis of the proposed heating system options. The energy use costs of the various options are only one aspect of the economic impact the systems might have. It would be relevant to complete a life cycle cost analysis of the various systems being compared.

Furthermore, additional heating equipment should complete the analysis such as heating water coils, heat pump, solar thermal panels, gas heating, etc. Different control options for the airflow rate and temperature could also be evaluated for each of the systems. Having one zone determining the system requirements is perhaps not the best option. A system that calculates the average load for the two greenhouses and adjust the air temperature set point consequently might lead to improve response both in terms of comfort and energy use.

It would also be interesting to analyze the characteristics of the supply air distribution systems. The 3.5 m^3/s system maximum airflow rate could certainly results in very high speeds within the system. It would be important to verify that the distribution speed at the plants level is within the recommended values as this could create too much stress or damage severely the plants (ASHRAE 2007).

Another aspect that has been overlooked in the modeling of the building is the air distribution in the zones. Because the model is simple and small, it would be interesting to carry out a CFD analysis to observe, among other things, the convection airflow specific to heating systems or the effects of passive ventilation.

One of the main difficulties of this study was to determine the energy intake of the plants (sensible and latent heat contribution, fresh air requirements). It would be interesting to propose design guidelines for different types of crops production. This could be supported by a more complete review of the available literature and the coupling of different plant models to achieve more realistic representation of the greenhouse behaviour.

Finally, several passive measures could be analyzed and compared. Some studies have already been carried out on energy saving measures for standard commercial greenhouses (Vadiee and Martin 2014). The proposed methodology measures could serve as a starting point to be applied to the proposed case under study.

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