

Anwar, M.; Rasul, M. G.; Khan, M. M. K.

Article

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Performance Analysis of rooftop greenery systems in Australian subtropical climate

M. Anwar^a, M.G. Rasul^{a,*}, M.M.K. Khan^b

^a School of Engineering and Technology, Central Queensland University, Rockhampton, Queensland 4702, Australia

^b School of Engineering and Technology, Central Queensland University, Melbourne, Victoria 3000, Australia

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Abstract

This paper presents the performance analysis of an extensive rooftop greenery system (green roof) in buildings in the Australian Subtropical climate, both experimentally and computationally. The impact of green roof systems on building thermal performance, energy consumption and energy savings are examined and compared with a non-green roof system in both experimentally and using computer simulation software called DesignBuilder (DB). For the experimental study, a shipping container with a green roof was converted into an office building. For comparison purposes, another shipping container of the same dimensions without a green roof layer was constructed and decorated in an identical way to the green roof container. Two computational models, one for green roof and other for non-green roof were developed. A 4 °C temperature difference between the green roof and non-green roof containers was observed on a typical summer day. For the green roof, the maximum variation between the simulated and measured data was found to be 5% for temperature, 7.5% for humidity and 9.4% for energy consumption. The study found that an extensive green roof on a building in the Central Queensland sub-tropical climate (Australia) can achieve energy savings of 13.65% (simulated) and 11.70% (measured) compared to a non-green roof.

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Keywords: Green roof; Subtropical; Thermal; Energy consumption; Design builder

1. Introduction

Australia is one of the largest polluters on per capita basis, generates 1.3% of total global greenhouse emissions each year [1]. The energy sector (stationary energy, transport and fugitive) is responsible for 76.9% of Australia's greenhouse gas emissions [2]. Electricity generation is the biggest offender (35%), as it relies heavily on burning coal for power. As the coal-dependent power generation of Australia produces a significant amount of greenhouse gas emissions, efficient operation of air conditioning systems in buildings has become more essential. However, it is an expensive choice to control hot humid temperatures in summer especially countries in the subtropical zone. A

* Corresponding author.

E-mail address: m.rasul@cqu.edu.au (M.G. Rasul).

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rooftop greenery system (green roof) acts as an insulation barrier, where plants reduce the solar energy reaching the roof and evapotranspiration further cools the green roof as the heat evaporates water from the growing medium and plant surfaces, resulting in cooler temperatures beneath the surface. A rooftop greenery system is one of the potential energy conservation measures. Greenery systems for buildings represent a promising new technology that has the proven potential to provide multiple private and public benefits. They have measurable structural, environmental, psychological, health and other benefits for building occupants [3]. They can reduce CO₂ emissions (27% in summer and 19% in winter) from air conditioning [4,5]. A study conducted at Michigan State University in 2009 showed that the inclusion of living roofs in Brisbane could reduce at least 100,000 tonnes of CO₂ per year, equivalent to removing 909,880 cars from the Australian continent [6]. While estimates of the cooling effect of living roofs vary greatly according to climatic and regional differences, reported cooling effects can be up to 20 °C [7]. However, their design and performance varies with each region, orientation, structure and climate. Because of this uncertainty, and lack of tested exemplars, designers and developers hesitate to use them. Green roofs have been around for centuries, used on domestic houses in Northern and Western Europe. There has been significant growth of extensive green roofs in Western Europe and North America in recent decades, mainly through retrofitting to existing buildings. In comparison with other developed countries, green roofs in Australia are not a popular choice yet. The main reasons are lack of technical data, and relevant and reliable research into positive impacts in local communities in the Australian context; and people are not aware of the economic and environmental benefits of green roofs [8]. Besides, most studies and research have been conducted on the northern hemisphere and a substantial difference exists between the northern and southern hemisphere climates, therefore those experiences and technology could be problematic for use in a subtropical climate. This study assessed the potential benefits and performances of greenery systems in the Australian subtropical climate.

2. Green roof technology

Green roofs are a complex layered structure, which typically has four layers of construction-waterproofing membrane, drainage layer, fabric filter and growing medium along with green roof plant. A waterproofing membrane prevents the moisture intake into the building. A root barrier layer is introduced on the top of this waterproofing membrane that prevents roots from penetration into the roof. The next layer is a drainage layer. The drainage layer is typically made out of plastic profiled elements. It is designed not only to carry water runoff to the gutter but also to store water for the plants in dry session. A filter fabric is installed just on top of the drainage system to prevent the growing medium from washing away and hindering the drainage layer. The growing medium or substrate with plants sits on top of the filter fabric. This growing medium is a porous medium with minerals enriched with organic material, liquid water and water vapour. Generally, it is lightweight and made of clay aggregate or vermiculite with a high water storing capacity component. Depending on the depth of the growing medium and maintenance effort, there are two types of green roofs: intensive and extensive. An intensive green roof has deeper growing medium that supports complex vegetation like shrubs and small trees. An extensive green roof has a thin growing medium that can support only shallow rooting planting. The scope of this study is limited to the extensive green roof technology.

3. Materials and methods

The experimental green roof setup was installed in Central Queensland University, Rockhampton, Queensland, Australia. Two-6 metre long, identical shipping containers ($2.44 \times 2.44 \text{ m}^2$) were converted into an office space. A green roof setup installed on one of the container and other one remained bare roof. Those containers had same furniture layout with a glass (5 mm dark grey float toughened) window, a glass (5 mm dark grey float toughened) sliding door as entrance and a box type air-conditioner. The shipping containers were constructed with steel frames, fully vertical-corrugated steel sides and front wall, horizontal-corrugated steel double doors at the rear end, die-stamped steel roof and corner fittings. A 230 mm galvanised aluminium bracket was used for holding the green roof materials. This bracket was bolted onto the container roof. As shown in Fig. 1, the shipping container was converted into a green roof and a variety of green roof plants had been planted.

In subtropical region like Rockhampton, green roof plants must tolerate severe sun and hot temperatures with changes in humidity and moisture. It was necessary to select suitable plants that would survive on top of a steel structure. A range of local native plants, such as *Rhoeo*, *Helichrysum Italicum*, *Callistemon Captain Cook*, *Dianella little jess*, *Eremophila Maculata* and *Grevillea Obtusifolia* Gingin Gem were chosen for consideration. A time-controlled irrigation system was used to ensure the garden was watered once a day. The experimental data on

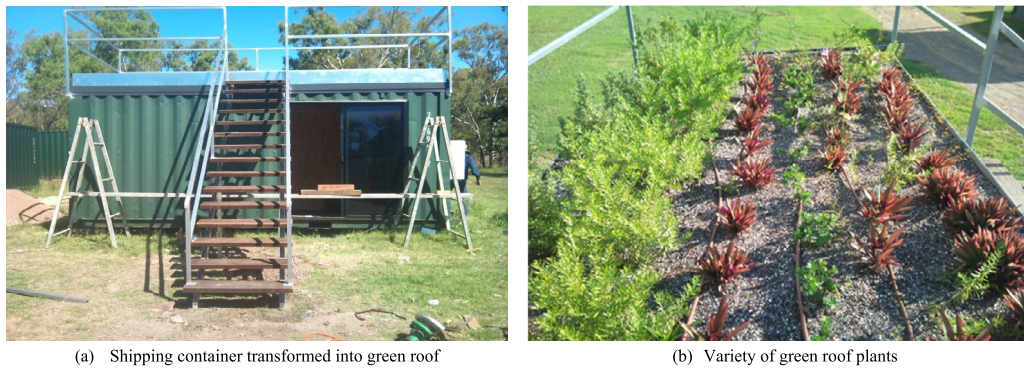


Fig. 1. Extensive green roof setup.

temperature, humidity and energy consumption was measured in 2013 for two months (December & January) of summer using those plants. Among all the plants, *Rhoeo*, *Helichrysum Italicum* and *Eremophila Maculata* were growing really well. About 50% of fractional vegetative coverage was observed. *Dianella little jess* also had a nice canopy but was found to be unsuitable for this harsh summer as some leaves were dried and the growth was very slow in summer. *Callistemon Captain Cook* was stable but a slow grower and had a smaller canopy. *Grevillea Obtusifolia Gingin Gem* was found totally dead, proven not to be a green roof plant for this climate. The growth of *Callistemon Captain Cook* and *Grevillea Obtusifolia Gingin Gem* in green roofs may need further research in order to understand their behaviour and hence improve performance. *Rhoeo* was found as an appropriate green roof plants and all the data was collected using *Rhoeo*.

4. Modelling and simulation

In this study, a physically based model of the energy balance of green roofs is implemented in a module incorporated in EnergyPlus (EP). An EP simulation is mainly based on input from text files, which increases the effort to define all necessary input data compared to engines with graphical user interfaces. The most advanced user interface is DesignBuilder (DB). Using EP, loads calculated on an hourly basis are passed to the building systems simulation module at the same time step. The block diagram of the building simulation model is shown in Fig. 2.

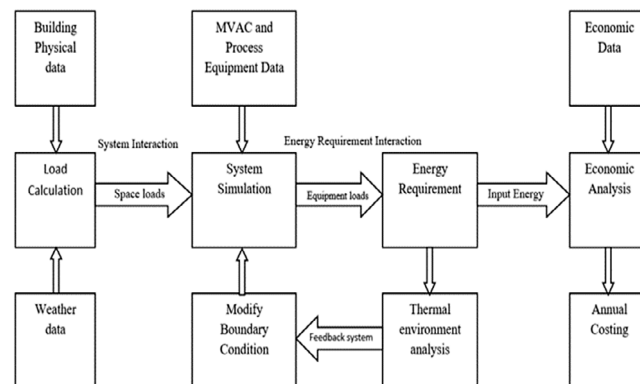


Fig. 2. Block diagram of building simulation model.

Using DB, a computer model for the prediction of thermal performance, energy consumption and thermal comfort characteristics of the green roof and non-green roof building has been developed in this study. DB uses hourly climate data to calculate annual energy consumption by direct modelling of 3D geometry. In this study, two building models are created. These models are identical in shape, decoration and construction material. The only difference is that one building model has a green roof layer on top of the roof and other model does not have any additional layer. A 3D model of the green roof building is constructed in DB interface as an actual replica of the green

roof container, with exact orientation, is shown in Fig. 3. The geometry of green roof model is exactly the same as non-green roof model. The Fig. 3 shows the central edit screen and left side navigation panel. The library component data bases for construction and data templates for activity, window opening, lighting and HVAC systems are located below the main menu bar which is enclosed inside the blue rectangle. There is another template area enclosed by the red rectangle comprising the heating and cooling design and simulation results of comfort profiles and energy consumption.

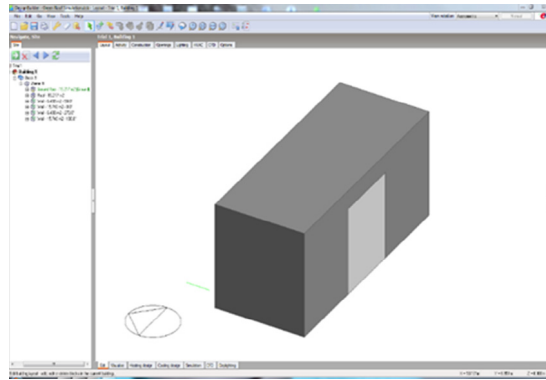


Fig. 3. Simulated view of the green roof or non-green roof building.

5. Results and discussion

5.1. Thermal performance

The thermal performance of a green roof refers to the thermal benefits it can bring to the building occupants. Some of these thermal benefits are reduction of energy demand for air conditioning, protection of the roof surface from exposure to UV radiation, and improved insulation for internal comfort. Data were collected when the air conditioner unit was switched ‘off’ and ‘on’ also for both the containers. Fig. 4(a) illustrates the temperature profile on a 24 h scale of the green roof and non-green roof buildings for a typical hot day in summer (January), when the air conditioner was ‘off’.

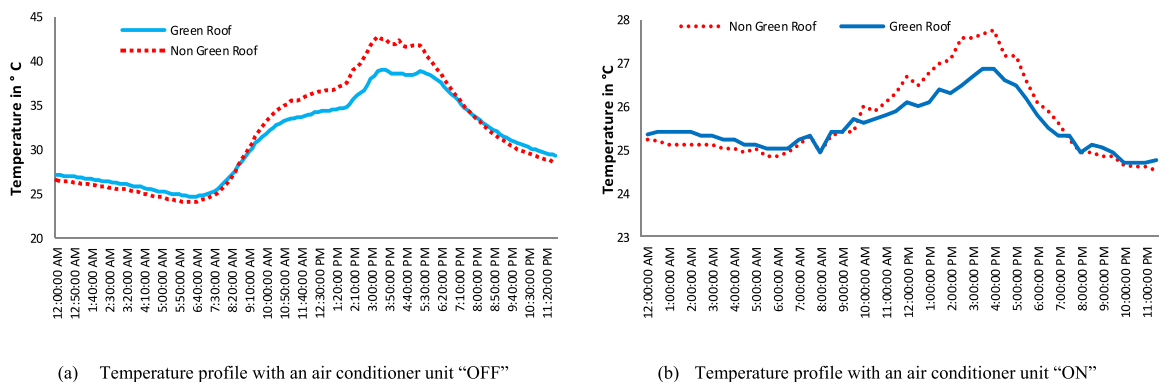


Fig. 4. Temperature profile of green roof and non-green roof containers on a typical summer day.

The temperature of the green roof building was higher than that for the non-green roof from 12:00 am midnight to approximately 8:00 am in the morning. The difference ranged from 0.5 °C to 0.7 °C. The non-green roof started to warm up as soon as the sun rose in the morning. Due to the high thermal conductivity of steel, it not only got hot quickly, it also cooled down quickly. From 8:00 am to 8:00 pm, the non-green roof absorbed much more solar energy than the green roof. Although the maximum temperature of that day recorded by Bureau of Meteorology (BOM) [9] was 31.7 °C, the non-green roof building recorded a maximum of 42.75 °C, which indicates direct

solar energy absorption. The maximum temperature difference between the two buildings was 4 °C which occurred at about 3:00 pm and this indicates that a significant amount of cooling energy can be saved. From 8:00 pm the non-green roof started getting cooler than the green roof and the maximum difference of temperature was recorded as 0.8 °C.

The temperature profile of both buildings on a typical summer day in January was also observed when the air conditioner was 'on'. The highest temperature was recorded as 36.6 °C by BOM. Both the air conditioners were set at 24 °C. Still, there was a difference of 0.88 °C in internal temperature. Fig. 4(b) shows the temperature profile when the air conditioner was on and the pattern of the temperature profile was similar to that when the air conditioner was off (Fig. 4(a)). Again, it can be seen that, from 8:00 am to 8:00 pm, the non-green roof absorbs more heat than the green roof.

5.2. Thermal comfort

The influence of humidity can play a part in the perceived temperature and thermal comfort of occupants. Normally, from 26 °C, relative humidity affects evaporation from the skin. More sweat evaporates from the body at lower humidity levels, whereas at higher humidity levels, moisture content is already high in the air, and it is hard to evaporate more sweat. In highly humid environments (relative humidity 70% to 80%), the situation is usually uncomfortable because the saturated air reduces heat loss through evaporation. A very dry environment (relative humidity 20% to 30% and less) is also uncomfortable because of its effect on mucous membranes. According to ASHRAE Standard 55 [10], the acceptable comfortable humidity level for a building with a HVAC system cooling at 24 °C is between 40% and 50%.

On a typical summer day, relative humidity under a green roof is higher than under a non-green roof. Fig. 5(a) shows the hourly relative humidity of both containers without the air conditioning on. There was a significant temperature difference of 4 °C between these two containers, as the green roof adds insulation value to the building. The non-green roof container's internal air temperature was recorded as 42.75 °C. The average humidity level for green roof and non-green roof containers was found to be 56% and 54% respectively. The relative humidity on a typical summer day in both containers is shown in Fig. 5(b) when the air conditioner was on. The green roof humidity level was higher than for the non-green roof container all the time, as expected. As the day progressed, the humidity level lowered from 70% to 45%, and started to rise again after 5 pm, settling at around 60%. According to BOM, the maximum temperature of the day was recorded as 33 °C, and the average humidity was 59%.

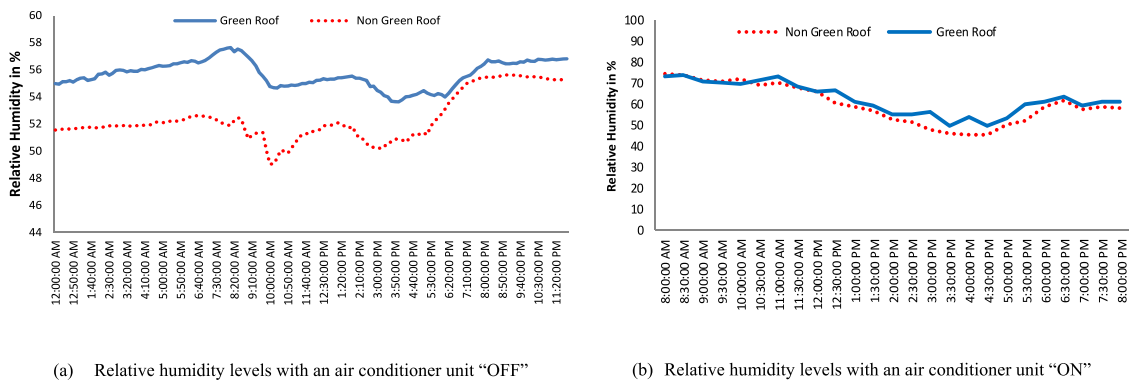


Fig. 5. Humidity levels of green roof and non-green roof containers on a typical summer day.

5.3. Energy saving

Energy consumption of a building can be reduced by implementing a green roof technology. Anwar [11] mentioned that the energy consumption for building air conditioning is higher in summer than winter and up to 11.70% cooling energy saving can be achieved by implementing green roof system in a building structure. Fig. 6 shows the energy consumption of air conditioning system in both containers on a typical summer day.

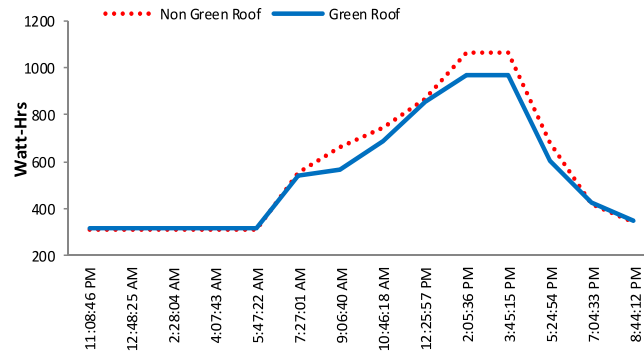


Fig. 6. Air conditioning energy consumption.

5.4. Validation of the model

Measured hourly indoor air temperature data on a typical day in December is compared with DesignBuilder (DB) simulated data in Fig. 7(a). The overall green roofs' hourly indoor air temperature differences between the simulated and measured conditions are found to be 5%, indicating a very good agreement between measured and simulated results. Measured average hourly indoor air humidity data on the same day of December is compared with DB simulated data in Fig. 7(b). The average measured humidity ranged between 60%–65% on this day and the simulated humidity ranged between 58%–66%. The difference between the simulated and measured humidity levels in occupied hours was found to be within 7.5%, indicating very good agreement between measured and simulated results.

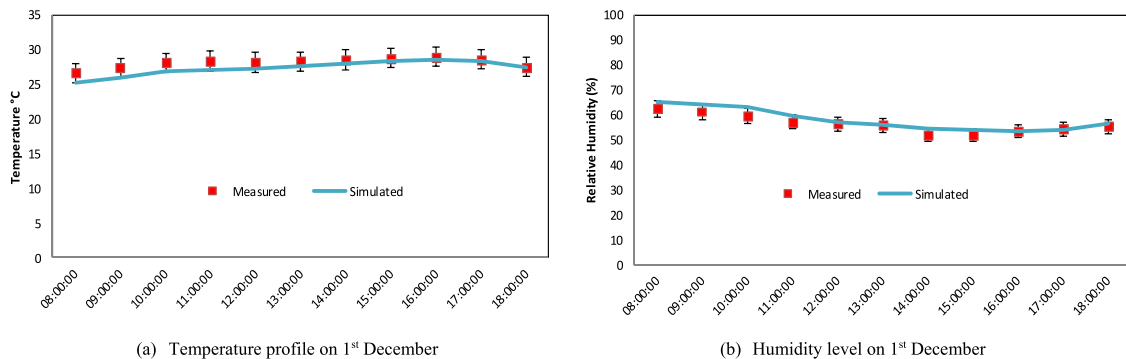


Fig. 7. Validation of green roof simulated and measured results on a typical summer day.

Blackbox energy analysers were installed into the experimental setup at the end of December. If these energy loggers were arranged at the peak of summer (December/January), better air conditioning consumption data could definitely have been recorded. The total electricity consumption was calculated by summing up the hourly consumption. The measured data are compared with the simulated data in Fig. 8(a). For 26th to 30th December, those five working days' actual average hourly energy consumption was 542 W, and the simulated consumption was 491 W for the green roof container. The difference between the values was found to be within 9.4%, indicating a reasonably good agreement between measured and simulated results. Fig. 8(b) shows a typical summer day's actual average hourly energy consumption was 586 W, and the simulated consumption was 541 W for the non-green roof container. The difference between the values was found to be within 7.68%, indicating a very good agreement between measured and simulated results.

From the simulations, the total energy required annually for cooling both green roof and non-green roof building was determined. The total energy required for the non-green roof was 4,302.41 kWh, while the total energy required for the green roof was 3,715.21 kWh. There is a 13.65% reduction in energy requirements with the additional insulation from the rooftop greenery system.

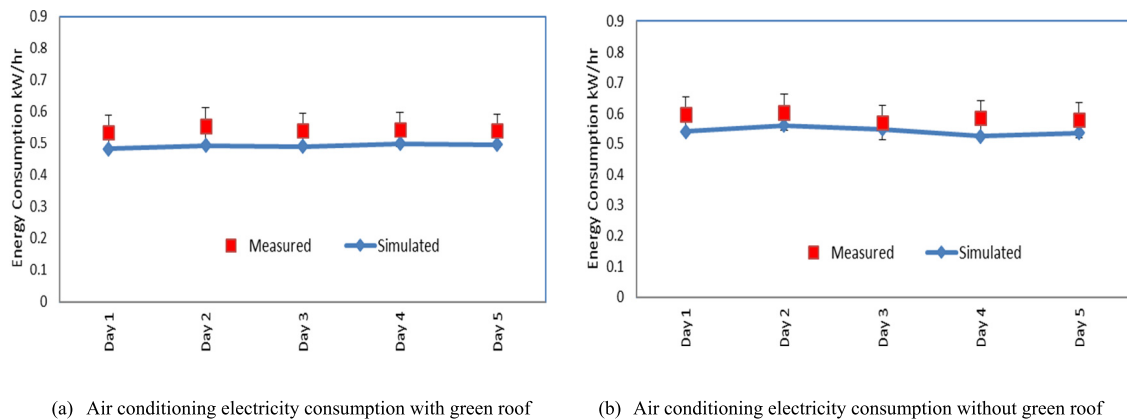


Fig. 8. Validation of simulated and measured air conditioning electricity consumption.

6. Conclusion

In this study, an extensive green roof system was investigated both experimentally and computationally for the summer season in subtropical Rockhampton in Queensland, Australia. The performances of the green roof are compared with a non-green roof system, in terms of thermal performance and thermal comfort. This study suggests that both *Rhoeo* and *Eremophila Maculata* plants are more suitable as green roof plants for their exceptional drought tolerance ability and better covering on the rooftop. Thermal performance of the green roof was analysed by comparing both green roof and non-green roof containers' solar heat absorption on a day when both air conditioner units were turned off. A 4 °C temperature difference was observed on a typical summer day. The simulated results of indoor air temperature, relative humidity and cooling energy consumption are compared with on-site measured data for both containers. In general, a satisfactory agreement was found. The difference between simulated and measured humidity levels in occupied hours is a maximum of 7.5% during summer. The simulated temperature profiles are within 5% of the measured value for both containers. The simulated values of energy consumption by air conditioning units (for both green roof and non-green roof models) during weekdays are compared with the BlackBox metred readings, and they are within 9.4% and 7.68% of the measured values of green roof and non-green roof containers respectively. The study found that an extensive green roof on a building can achieve energy savings of 13.65% (simulated) and 11.70% (measured) compared to a non-green roof.

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