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Abstract. Structural-spatial form and urban land use are among the main transformative fields of action of cities. Quality of life and environment, identity and individuality as well as participation in local society are significantly influenced by urban surfaces. Most urban surfaces have so far been designed for the long-term fulfilment of individual purposes, but offer greater scope for design in terms of functionality and adaptability, quality and efficiency. It therefore makes sense to develop, evaluate, technologically expand and test the potential of urban surfaces in terms of building physics as a whole. In view of growing stress on urban structures due to climate-induced influences, such as flooding, extreme weather conditions or heat islands, new possibilities, processes, systems or materials are needed to improve resilience. The article presents exemplary developments that can be supplemented and combined. Hydroactive surfaces can buffer rainwater and release it with a time delay to reduce heat and flooding equally. Green façades improve city climate and air quality. Sound-absorbing façades reduce inner-city noise. Innovative transparent foil enclosures provide equally visibility and an optimum weather protection of objects to be protected throughout the year.

1. Introduction

Essential transformative fields of action for cities are their structural-spatial design and urban land use. They are of particular relevance for the sustainable development of cities and urban districts, as they have a decisive influence on the quality of life and environment, on the identity and the participation in local society. At the same time, there are inseparable interactions between the design and use of urban areas and other fields of action, including resource and energy efficiency, climate resilience and mobility. The focus of most settlement, traffic and, above all, building surfaces has so far been solely on the long-term fulfilment of individual purposes. For the exploitation of a multitude of further design and action options, it is necessary to unite the aspects and actors that originate from all parts of urban society in a structured and moderated interdisciplinary and interest-spanning process. The fact that local authorities are highly affected by permanent climate changes and extreme weather events alone makes it clear that these challenges can only be met with coordinated contributions. These contributions include the holistic development and technological expansion of the building physics potential of urban surfaces. Figure 1 illustrates the effects and interactions in the context of the current situation and design goals.



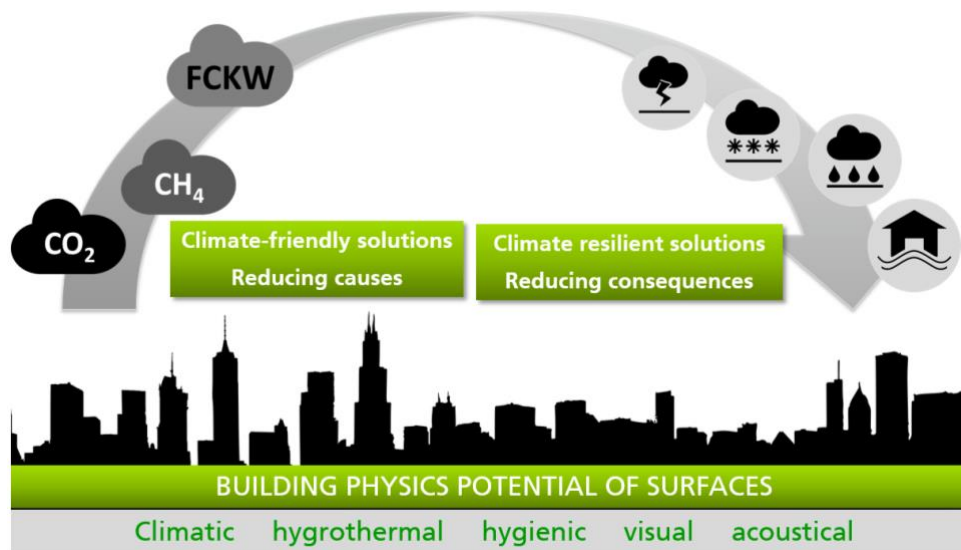


Figure 1. Building physics potential for the design of urban surfaces with climate relevance and for sustainable quality of life and environment in cities.

The current state of knowledge clearly and frequently demonstrates the need for action, but also shows concrete options for action that can be used effectively and economically, e.g. to react to specific consequences of climate change and to the increased dynamics of weather phenomena (water, snow, temperature). In practice, however, there are often barriers that are cross-use, cross-interest and cross-disciplinary. In order to be able to extend the system concept to large urban surfaces, e.g. to include aspects of urban safety (disaster and fire protection), systematic physical land management is necessary, as illustrated in Figure 2. Sustainability is the basic principle and standard of the design.

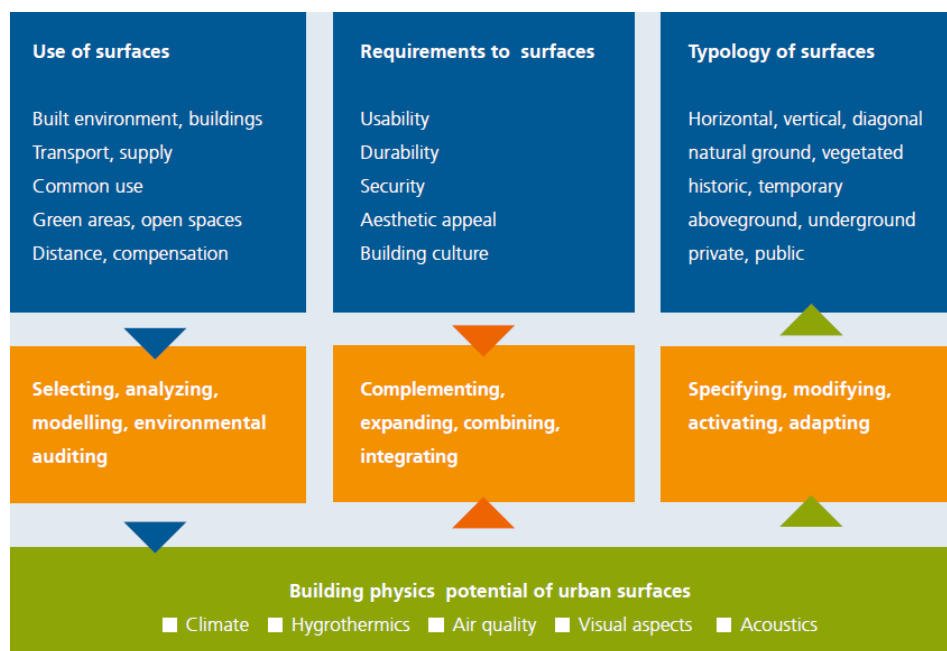


Figure 2. Systematic consideration and treatment of urban surfaces in the sense of physical land management.

The experimental determination of the properties of urban surfaces, the (quarter and city) model description with planning tools and, of course, the evaluation were and are the subject of research and development in order to develop the building physics potential. The Fraunhofer IBP is working on these topics since a couple of years in several projects. Currently there is a comprehensive project running at the IBP to develop both solutions for an enhanced climatic resilience and an improved sustainability of urban surfaces. Exemplary results of the IBP developments and their interrelated consideration are reported here. The examples given are chosen to show the wide scope of options.

2. Hydroactive traffic and open spaces

In metropolitan areas, the proportion of sealing increased to over 90 percent of the total area, which increases and accelerates precipitation runoff on the one hand and reduces the amount of water available for evaporation, latent cooling and groundwater recharge on the other hand. Since the lack of buffer areas leads to overloading of the sewer system, municipalities can limit the maximum discharge donations from properties and, for example, prescribe retention options on the property [1]. However, particularly in highly dense settlement structures there is often no space for open indentations, e.g. trough-trench systems with high infiltration and evaporation rates. Therefore, urban surfaces are in demand which serve to prevent heat and flooding equally [2]. One approach is the so-called "sponge city" principle [2] [3], in which urban surfaces are increasingly used for the intermediate storage of precipitation. The aim is to approximate the water balance of built-up areas to that of undeveloped areas, i.e. essentially to reduce the peak discharge values after heavy rainfall events and to increase the proportion of local evaporation and infiltration for groundwater recharge in the urban water cycle.

The horizontal roof and traffic areas, which have so far been largely fallow, as well as selected façades are of particular importance for potentially hydroactive areas [4] [5].

For decades, paving surfaces have also been able to be designed as infiltrable coverings. Usually, paving structures with a porous structure or seepage openings with a regular profile are considered. Alternatively, the joint between the paving stones is filled with coarse-grained material. In order to enable complete drainage in the vertical direction, all layers in the substructure must be permanently permeable in addition to the surface layer. Due to the resulting lower mechanical load-bearing capacity, it is only used on traffic areas with low loads, e.g. service roads, pedestrian zones and permanently used parking areas with low truck and bus traffic [6] [7]. So far, initiatives to use traffic areas as summer urban heat sinks have been rare [8]. While commercial products are not yet available, field measurements show that a temperature reduction of the order of ten Kelvin is possible, depending on the boundary conditions. This corresponds approximately to the temperature difference between a dry concrete surface and a grass area at noon. Figure 3 shows a field test with different water-storing concrete pavements.

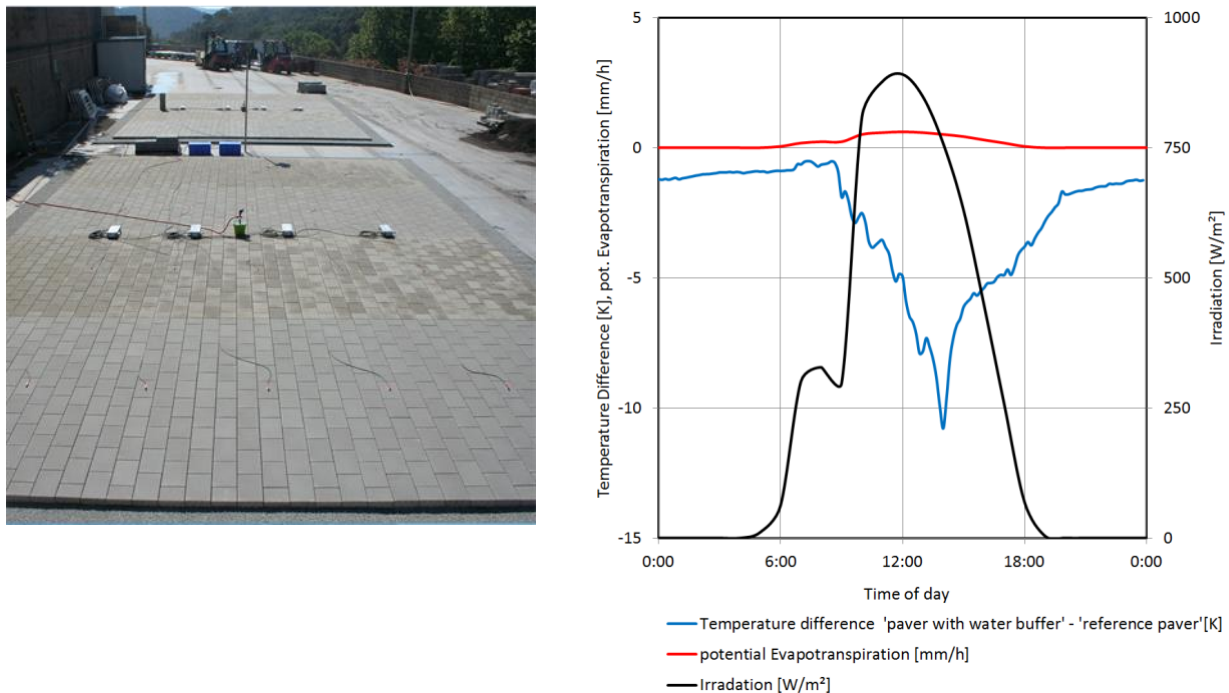


Figure 3. Field test with different water-storing concrete pavements (left: test field, right: measured temperature reduction of a storage stone compared to a standard concrete paving under summer conditions [8]).

3. Greening of façades

With the "Weißbuch Stadtgrün" [9] the political goal is pursued to promote green in the city and thus also green buildings and façades. An obvious argument is the effective medium to long-term CO₂ binding and thus the contribution to climate protection.

In the manner of a "natural air-conditioning system", evapotranspiration through vegetation can have a cooling effect in the sense of reduced summer heating, sort of reducing heat stress in urban areas [10]. Comparative measurements of conventional and greened façades show that the latter have a cooling effect in summer and an insulating effect in winter, as well as balancing the humidity directly in front of the wall. For example, the evapotranspiration of an 850 square metre "living wall" is approx. 1,800 liters with the corresponding cooling capacity [11]. Façade-bound greenery thus reduces the effort required for air-conditioning of the buildings because it keeps them cooler.

In terms of air quality, model observations [12] show a reduction of nine percent NO₂ and 13 percent PM₁₀ (Particulate Matter $\leq 10 \mu\text{m}$) in incoming air pollution when large-area green walls are placed in street canyons under average conditions. Within a street canyon, reduction values of up to 15 percent NO₂ or 23 percent PM₁₀ are possible, which can increase by up to 40 percent for NO₂ and 60 percent for PM₁₀ at low wind speeds. Data on concrete filtering performance of climbing plants are only available in isolated cases. In the case of ivy (*Hedera Helix*), for example, this is four to 8.4 percent of the total dust in the vegetation period or 1.8 to 3.6 percent per year. Of these, 71 percent are smaller than 15 micrometers and only ten percent smaller than 5 micrometers [13] [14]. With the Boston ivy (*Parthenocissus tricuspidata*) a binding of up to 80 percent of metals from the coarse dust was determined [15]. All these results prove that green façades can cause a local reduction of dust pollution. The examples also show, however, that systematic investigations with practical relevance are urgently required in view of still incomplete information on the potential effects.

While green roofs are already comparatively well developed and numerous systems for the most varied tasks and requirements are already established on the market, there is still a need for optimization

for green façades. Many systems are fragile and also costly to install and maintain. Extensive greening must be carried out with site-specific plants, e.g. for certain mosses, and must include targeted control and promotion of surface colonization. This is the only way to achieve a visually appealing growth that is regularly and homogeneously distributed. At the same time it promotes the native flora and expands the niche offer for numerous animal species.



In addition to innovative design and implementation, a key to success also lies in selecting the right plants for the respective application and planning situation. For example, mosses with up to 30 times larger surface areas have a higher fine dust binding potential than many grasses.

Since further investigations are necessary, a new method is currently being developed to settle moss on building surfaces. First results are both promising and essential for future development steps. The condition of the test specimens in Figure 4 after winter weathering in the open shows that the moss was able to establish itself on the surfaces protected from driving rain. The used building material, on the other hand, has obviously been strongly affected by frost-thaw changes, which is why further investigations with different building materials are necessary in order to find an optimal correlation here.

Figure 4. Three-dimensional test specimens of 10 by 10 by 10 cm AAC block and planted with moss (two different shapes). Test specimens before (top) and after winter weathering (bottom).

4. Sound absorbing façades

The unchanged high attractiveness of cities also leads to increasing acoustic demands on urban systems and structures. With regard to the perception of sound in an urban context, the reflective behavior of façades is the main focus. In distinct street canyons, the hard building surfaces amplify all sound events, but of course the shielding effect of buildings is also perceived. Before functionally extending façades to influence acoustics, especially in noisy urban spaces, it is important to emphasize that this should never be at the expense of their function as sound-insulating building envelopes. In practice, there are still deficits and development needs. The acoustic functionalization of façades certainly cannot solve urban problems on its own. In order to take up the proof and the economic efficiency of acoustic façade functions for urban areas, a systematic consideration is the first step. The practically relevant acoustic categories can be summarized as follows:

- Sound generation / sound radiation: Today, façades emit considerable and above all completely expendable noises. Ventilation openings, movable sun protection systems or wind noises on acoustically sensitive façade elements are just a few examples of avoidable noise exposure.

- Sound screening / sound diffraction: These terms are essential for the already mentioned shielding effect of buildings in urban environments. There is the possibility of a targeted influence on the propagation of urban sound through structured façades, balconies, overhangs, roof connections and the like.
- Sound reflection / sound diffusion: Together with shielding and diffraction, they contribute to the amplification and distribution of sound. On the other hand, however, there is a great variety of elements, structures and urban design scope to consciously direct sound into less sensitive areas, even if it cannot be stopped or absorbed.
- Sound absorption: The actual reduction of sound energy once generated only is possible by absorption or dissipation of sound waves. Materials, layers and structures as well as openings and gaps offer numerous possibilities without having to invent a new façade. Almost all façade types can be functionally upgraded or converted to achieve high sound absorption levels.

A concrete example of a possible modification is the "rear-ventilated curtain façade". The system has been established for a long time and proven in practice, is characterized by a high degree of design diversity, is accepted by building owners and architects and is in itself unproblematic in terms of building physics functionality (moisture, heat and fire protection). However, the goal-oriented implementation in practice requires knowledge of the optimum relationship between flow resistance and other properties of the (outer) layers. Figure 5 schematically shows a façade structure with a sound-permeable (e.g. perforated) outer layer and its sound absorption if three different underlay sheets are used in front of the insulating material. The main difference is the flow resistance of the underlay variants, which certainly still meet the requirements of DIN EN ISO 13859 [16]. The sound absorption coefficients show the effect of clever modification of individual parameters. If typical inner-city noise spectra are used, highly absorbent noise protection façades can be achieved with variant 3 in Figure 5.

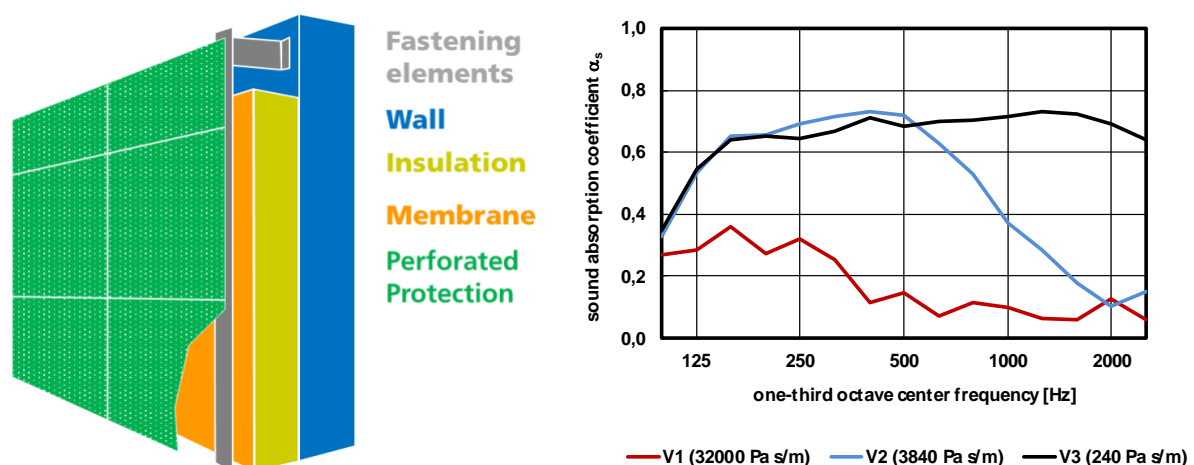


Figure 5. Acoustically modified, rear-ventilated curtain façade (left: schematic structure, right: measured sound absorption coefficient at vertical sound incidence and use of 3 underlays with very different flow resistances).

Based on this sound absorption effect, its impact on the urban environment can be calculated and evaluated. For the exemplary quantification of the potential, Figure 6 shows the building situation with buildings aligned parallel to the source (motorway, dark blue area on the bottom right), flanked by vertically positioned buildings and a side street. The standardized frequency-dependent calculations were carried out according to DIN ISO 9613-2 [17], the street (traffic figures) was characterized as a line source in octave bands with noise spectra from pass-by measurements. Geometry and topology are based on real, in detail simplified data and the façades were mathematically clad with sound-absorbing

material. The results allow the comparison of weak absorption effect, e.g. a normal exterior plaster (Figure 6, left), and highly absorbing ($\alpha_w \geq 0,75$) material (Figure 6, right), as e.g. with the layer variant 3 according to Figure 5. The level differences are clearly recognizable and concern not only the individual points (figured level values), but considerable zones of the area.

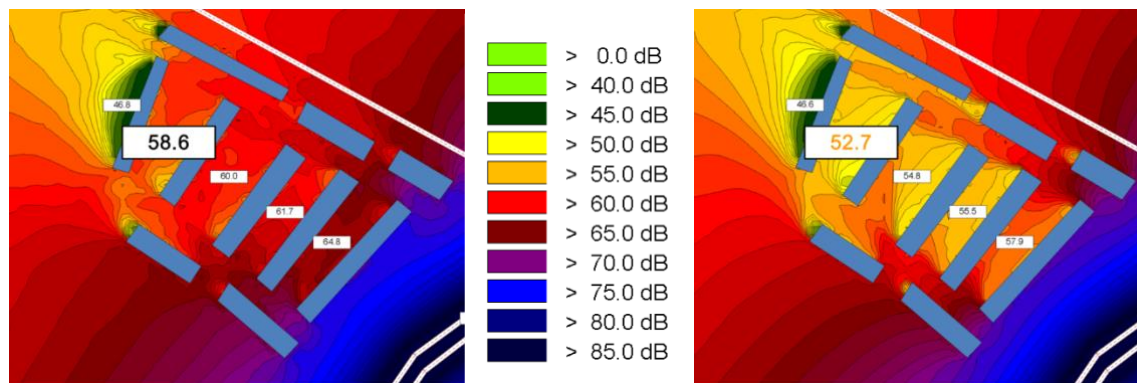


Figure 6. Sound immission calculation with low (left) and high (right) sound absorbing façades of the buildings. The single values in the maps are sound pressure levels (sum levels in dB(A)) at selected points.

Of course there are still some questions, e.g. after the comparison with noise barriers or after the additional costs. The answers will be differentiated and will lead to concrete advantages and disadvantages depending on the situation. With a view to the future, it is therefore important to recognize, evaluate and treat the acoustic environmental influences in almost all, including urban, living spaces.

5. Transparent enclosure systems

Every autumn thousands of fountains or stone sculptures are hidden, mostly under wooden enclosures, to protect them from the winter climatic conditions. However, this measure makes a large number of culturally valuable objects invisible for almost half the year. These temperature-damping opaque enclosures offer a comparatively constant indoor climate, but with a consistently high level of air and material humidity and without completely preventing frost-thaw changes, which contributes to the damage to the cultural assets. The solution of using transparent enclosures made of a steel and glass construction to ensure the visibility of the objects to be protected enhances the quality of the urban space. Nevertheless, on the one hand these constructions are associated with increased costs due to the choice of materials and the logistical effort involved, on the other hand the combination of glass housing and solar input creates a "greenhouse effect" which results in high fluctuations in temperature and humidity and puts considerable strain on the object to be protected [18], not to mention possible glass breakage.

Scientists from the Fraunhofer Institute for Building Physics IBP and the Technical University of Munich have therefore developed and investigated an enclosure system made of transparent membranes which, by damping the amplitudes of temperature and relative humidity, enables a climate favourable to the object to be protected [19]. Further goals of this system are, among other things, the avoidance of the essential damage mechanisms for stone objects, especially frost-thaw changes at high material moisture levels, thermohygric deconsolidation and organic growth as well as favourable assembly, transport and storage properties and sufficient durability. In addition, the design should pay attention to optimum regulation of the ventilation system. When the ventilation is too high, the external climate also becomes apparent in the interior and leads to moisture ingress and condensation on the stone, whereas too little air exchange can trigger a permanently high air humidity and consequently frost splitting and organism growth.



The transparent enclosure system under investigation consists of a framework with braced stainless steel profiles, into which a prefabricated polyvinyl chloride foil cover is suspended. This system is characterized by various advantages. On the one hand, it can be easily dismantled into its individual parts and reduced to a small storage volume, and on the other hand, the support frame has good durability. In addition, the film is easy to replace in the event of attrition and, among other things, offers high tear and UV resistance combined with "non-crease" transparency even after repeated construction and dismantling. In addition, the high moisture content of the material at the time of enclosure can be dissipated to the outside via heating due to solar radiation in conjunction with controlled air exchange, while moisture entry by re-condensation is prevented.

Figure 7. Newly developed foil enclosure in field test.

The results of the measurements carried out prove that with these systems a faster material drying is achieved than with previously used opaque wood enclosures. In addition, organic growth is largely avoided and the material to be protected is kept dry. The innovative transparent foil enclosures with controlled ventilation are an interesting alternative to the opaque wooden enclosures currently in use especially because they provide equally visibility and optimum weather protection of the fountains or stone sculptures that characterize the cityscape throughout the year.

6. Outlook

Although the challenges of urban systems are not equally distinct in all cities, the impact of elementary urban structures can be found everywhere. This also includes the chronic and acute consequences of climate change at the local level, such as water shortages or flooding, unusually hot and cold weather conditions, heat islands and haze bells. Urban surfaces will play a major role in the reaction and transformation of cities, and their building physics efficiency is significantly higher than it has been exploited yet. In the future, innovations and investments will be just as necessary as regulations, incentives and information. The aspects and examples presented show that the building physics of urban surfaces can make valuable contributions to this.

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