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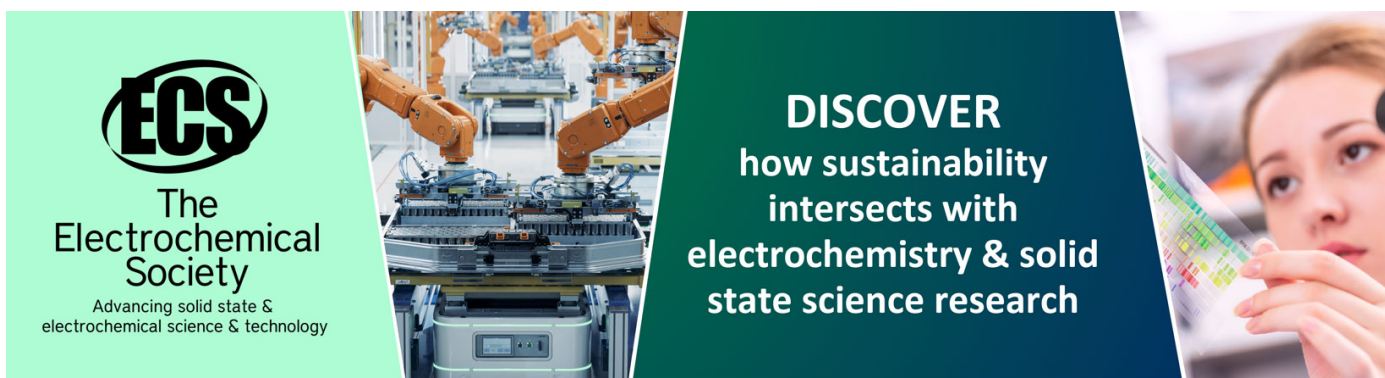
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Assessing the Indoor Conditions of a 3rd Century AD Roman *Domus* by Dynamic Energy Simulation and Comparison with Vitruvian Hypothesis: Preliminary Findings

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Abstract. Roman best practices concerning construction technology were well consolidated and implemented in ancient times. These are traditionally belonging to Vitruvius, who coded the classic rules on architecture. Amongst these, the destination of use of the different rooms is paramount, especially in respect to the orientation of the building. Dynamic energy simulation software is a tool of proven effectiveness and of widespread diffusion in the field of building engineering. It is primarily used to evaluate and foresee the effects that building stratigraphy, thermal loads and HVAC systems have on the indoor thermo-hygrometric conditions. In this study, such tool has been used to investigate ancient buildings, basing the analysis on reliable hypothesis about the original construction, partially assumed if the upper structures were missing, on the actual stratigraphy obtained from archaeological remains, and on the supposed ancient climate condition estimated from literature on ancient climate and archaeological evidences. The analyzed case study is a Roman *domus* that dates back to 3rd century AD, located in Piazza Nogara (Verona, Italy). The proposed method allows evaluating the indoor comfort conditions that occurred when the building was inhabited. Furthermore, simulating different building orientations, it is possible to verify if the actual destination of use of the rooms is the very best from an indoor microclimate standpoint.

1. Introduction

Dynamic energy simulation consists in a software which can replicate the building geometry and the physical characteristics of the construction itself, in order to model its energy and thermal behaviors under imposed external conditions. It is capable to evaluate the effects that a building stratigraphy has on the indoor thermal conditions, the thermal loads, and assisting the design of the HVAC systems. Recent researches have used such tool for evaluating the microclimate conditions for conservation purposes of historical buildings [1,2,3]. For this reason, it could be of great interest to use it in studying ancient buildings that do not exist anymore, e.g. for archeological research in validating a few of the many unanswered questions and the use of buildings by the original inhabitants. On the other hand, it is paramount to consider that the outcomes of the dynamic energy simulation are strictly dependent on the reliability of the input data of the building and of the considered boundary conditions. Moreover, the vast majority of the software functions and libraries were made specifically for modern buildings, so an adaptation has to be made whenever the dynamic energy simulation tool is used for different purposes.



1.1. Roman house in Vitruvius and in Northern Italy

In the VI book of the *De architectura* Vitruvius (end of the 1st cen. BC) describes the theoretical model of the élites's *atrium* house (first examples in Rome, 6th cen. BC). After the entrance (*vestibulum* and *fauces*), was the *atrium*, expanding laterally into the *alae* and then the *tablinum*; next to the exedras, there were the closed rooms, used mainly for the rest (*cubicula*) and the banquets (*triclinia*); at the bottom of the house or laterally there was a vegetable garden (*hortus*), then monumentalized as *peristylum*. Since the 2nd cen. BC, deep changes affected this architecture: the house become wider, more articulated and separated. *Triclinia* multiplied in number. The distinction of areas for the different seasons, according to the criterion of convenience, was set. Vitruvius suggests the most suitable orientation for the different season of use: open towards the north the summer *triclinium*, to the west the winter one, to the east the spring and autumn one. In Northern Italy, the *domus* shows a singular weaving of typically Roman solutions associated with other choices due to local traditions and climatic factors. For example, the uncovered areas present, on average, a smaller size and a paved floor instead of a garden; in some houses, direct internal communications among the rooms existed. A characteristic aspect is the inclusion of heated rooms in the residential area, which also radiated heat to adjacent rooms; widespread in the 2nd cen. AD, in addition to simpler heating systems consisting of mobile braziers [4].

2. Case study: the *Domus* of Piazza Nogara in Verona

The ancient residential building is known in literature as "*Domus di piazza Nogara*" due to its location in the modern Nogara Square in Verona, Italy. The house has been almost totally excavated starting from 1976. The floors, the foundations, the threshold of the doors, and a variable elevation of the walls still exist and are now visible under a building hosting a Bank. The *domus* was erected during the Augustan age, over an area of 20 m x 19.60 m [5]. Its use lasted until the 6th cen. AD, of course with architectural changes. Here, we consider the situation of the 3rd cen. AD, period during which some main improvements were realised. As shown in figure 1, the entrance is likely in room 1. Contiguous at the entrance are two small rooms (2 and 3), passing to the court (4). Around the co

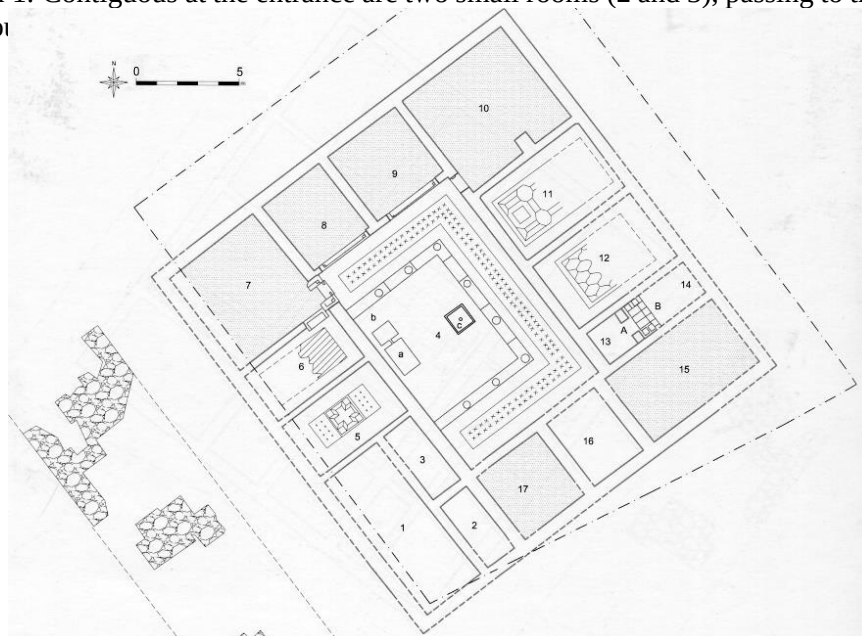


Figure 1. Planimetry of the *domus* in 3rd century AD

The two central rooms on the north (8 and 9) have two large openings on the court. A small heating system is present in room 14, perhaps a small *sauna* or a bathroom; 14 was close to the kitchen (15), as suggested by Vitruvius and frequently found in archaeological evidences. The rooms 5, 6, 11 and 12 in this period are covered with mosaics, the colonnaded porch is enriched by a new mosaic, and the court

equipped with a marble fountain. It should be pointed out the raising of the floor level of the rooms 11 and 12, probably in order to facilitate the passage to the heated room.

2.1. The hypocaust room with *praeefurnium*: ancient sauna, radiant heating system or both?

During the 4th or 3rd cen. BC the kitchen appeared in the Roman architecture, giving the fire a more specific function [4]. Other devices were used for the heating in the winter period, i.e. braziers. A technical innovation took place between the end of the 2nd and the beginning of the 1st cen. BC, when an indirect heating system was introduced: the hot air circulated under the floors and inside the walls, keeping the rooms at a constant level of heat. An oven was used to radiate hot air (*praeefurnium*): this worked underground in a ventilated area designed to receive a certain amount of fuel. There was a simple opening in the wall, with a metal door with a ventilation opening, preceded by an area where the ashes were collected. The *praeefurnium* was fed with charcoal, whose heat expanded into the underside of the floor, the *hypocaustum* (fig. 2 and 3), and then propagated through vertical conduits. The *hypocaustum* was an empty space, covered by a suspended floor generally lying on brick pillars, formed by square bricks of 20 cm per side, at a regular distance of 60 cm each other. Above these were large bipedal bricks, on which the actual floor rested. The suspended floor had a similar structure to all the floors (lower layer in coarse *cocciopesto* 15/20 cm thick, upper in finer mortar covered by a marble paving or a mosaic). The total thickness of the floor was 30/40 cm which, added to the height of 50 cm of the pillars, gave a total height of about 80/90 cm. The hot air was also used to heat the rooms through the walls, provided for this purpose with an interspace (empty space between the bearing wall and the wall), reaching the ceiling; it was very useful even when the heating system was not operating, as the layer created between the walls kept the temperature high. In the second half of the 1st cen. BC the hypocaust system is found in domestic baths, always in prestigious houses [6]. This solution was used also in residential rooms and had a significant role in Northern Italy, because of the latitude [7]. The examples spread out throughout the entire area, although they are more frequent in the eastern region.

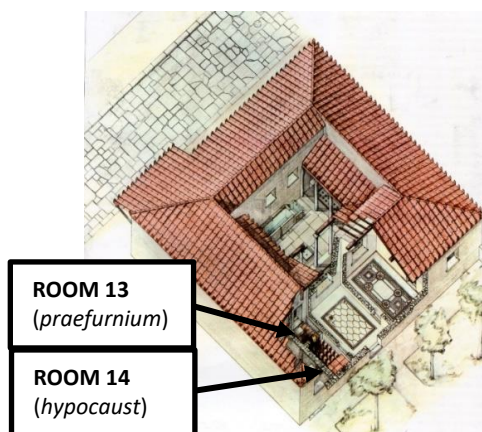


Figure 2. Isometric view of the *domus*, depicting the reconstructed architecture of the 3rd century AD building phase.



Figure 3. Remains of the *praeefurnium* (room 13). The *pilae* in room 14 are barely visible beyond the fireplace location and partially covered under the foundations of the modern building.

3. Methodology

Archaeological hypothesis have been investigated using an energetic model of the building, as close as possible to its configuration during the 3rd cen. AD. Specifically, has been evaluated if the air temperature in room 14 was high enough for *sauna*-related uses, and if the thermal effect was enough to advance reliable hypothesis of a double-use as heating system for the adjacent rooms. Furthermore, the assessment of the thermal comfort for each master's room during the whole year could validate the *Virtuvian* hypothesis about seasonal changing of the rooms for *triclinium*. The archaeological reconstruction helped in assessing the building geometry and the missing parts of the *domus*, such as windows, doors, ceilings and roof cover. Wherever possible, the direct measurement of the ruins was carried out on site, e.g. the wall thicknesses.

4. Dynamic energy simulation

The *Domus* of Piazza Nogara was studied using the software TRNSYS® [8]. Building elements and geometry have been taken from architectural reconstructions. When data could not be obtained directly, typical values from the literature were used. The weather come from standard weather libraries [9] considered similar to the weather data of that period and place. The boundary condition for this evaluation are: Climate data, internal loads (a fireplace as *praeurnium*, considering an amount of 5 kg of common hardwood with a wood heat value of almost 15 MJ/kg burned at 70% efficiency [10], considering a 50% of convective fraction), and air infiltration (1.0-2.0 vol/hr).

4.1. Evaluation of the envelope stratigraphy and thermophysical properties of construction materials

The definition of the *domus* within the software takes into account the geometry and the thermophysical properties of each building element. If reliable databases of construction materials are not available, thus measurements on site [11,12,13,14] or on samples [15] are usually performed. The special nature of the case study implies the impossibility to carry out direct measurements, an indirect approach based on some existing remains based on the ratio between the building components of the walls was used. The external wall of the *domus* is 0.40 to 0.60 m thick and it is made of pebbles and mortar, brick fragments are very rare. Concerning the internal partitions, with a variable thickness ranges from 0.50 to 0.35m. In such walls, the presence of salvaged brick material is relatively greater compared to the external ones. Both wall types were covered with a layer (5 cm thick) of mortar on both sides. In order to evaluate the main thermophysical properties of the walls, an evaluation of the equivalent heat capacity c_{eff} , thermal conductivity λ_{eff} and volumic mass ρ_{eff} have been carried out considering the ratio between pebble stones and mortar and amongst pebbles-mortar-bricks respectively. For each of the three materials, reference values were taken from literature (table 1), while the thermophysical properties of the whole walls were approximated [16,17] as function of the ratio between the volume of pebbles, mortar and bricks in respect to the total volume of the walls.

Table 1. Thermophysical properties of construction materials of the walls of the *domus*.

Building material	λ [W m ⁻¹ K ⁻¹]	ρ [kg m ⁻³]	c [J kg ⁻¹ K ⁻¹]
Clay brick	0.5	1800	840
Pebble stone (porfid)	2.9	2200	700
Mortar (lime plaster)	0.8	1600	1000

The ratio values have been obtained starting from geometrically registered photographs of wall sections acquired on site. An iterative thresholding approach has been applied, tuned by a quantitative comparison between the thresholded luminance values versus a binary golden standard, in order to clustering each material (figure 4 and 5). Finally, the ratio between peaks of the images histograms allowed retrieving the ratios between the materials.



Figure 4. Photograph of an external wall section.

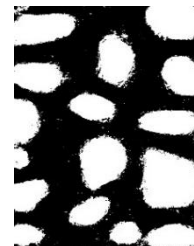


Figure 5. Geometrically corrected and binarized image of an external wall section.

The stratigraphy of the walls was computed in terms of thermal transmittance (U) (table 2), one of the main parameters describing the thermal insulation performance according to current standard of calculation of building envelope components [18].

Table 2. Heat transfer properties of typical walls of the *domus*.

Wall type	Outer layer Thickness [m]	Middle layer Thickness [m]	Inner layer Thickness [m]	U [W/m ² K]
External	0.05 (mortar)	0.6 (pebbles and mortar)	0.05 (mortar)	2.2
Partition	0.05 (mortar)	0.4 (pebbles, mortar and brick fragments)	0.05 (mortar)	2.7

Long lost building elements (wooden ceilings, clay tiles roof covering, single glazing/wooden frame windows, and wooden doors) were considered solely on an archeological basis, thus the properties were based on literature.

4.2. Estimation of the climatic conditions of north-eastern Italy in 3rd century A.D.

Roman Age climate reconstruction is possible, for the mean temperatures, through multi-proxies data analysis, e.g. historical literary and iconographical sources, palinology, analysis of tree rings, ice cores, etc. [19]. According to Charpentier Ljungqvist [20], the temperature history of that period is characterized by a Roman Warm Period (c. AD 1-300) and a Dark Age Cold Period (c. AD 300-800), as already suggested by Lamb [21] (figure 6). The 2nd cen. seems to have been the warmest in the last two millennia, with mean temperatures similar to ones of the 20th cen.; the subsequent cooling was not severe as the one occurred during the Little Ice Age. Ljungqvist [20] substantially agrees with the previous ones [21,23,24,25]. Following McCormick [19], an exceptional climate stability characterizes the first two centuries AD; Alpine glaciers were retreating and were relatively small, comparable probably to their 20th cen. extent. This situation begins to change during the second half of the 3rd cen. AD, when alpine glaciers slowly grows again [26,19]. Chen [27] substantially agrees with the above reconstructions, finding high stable temperatures until 90 AD, followed by a decreasing trend starting from the end of the 1st cen. AD, and suggests that the air temperature during the whole period was warmer than that of the 20th cen.. Esper et al. [28] agree with the general overview of the period as a succession of warm and cold episodes, including a peak warmth during the Roman times alternated with a severe cool condition during the 4th cen., with a difference during AD 21-50 of +1.05°C with respect to the 1951-1980 average: the warmest reconstructed 30-year period. Generally speaking, the historical sources seem to outline a situation of wetter climate, during the considered period, in South Europe and North Africa [29]; this could coincide with the detected hydrological trends in Spain's lakes as studied by Curràs et al.[30], where a period of enhanced moisture is reported during AD 160-370.

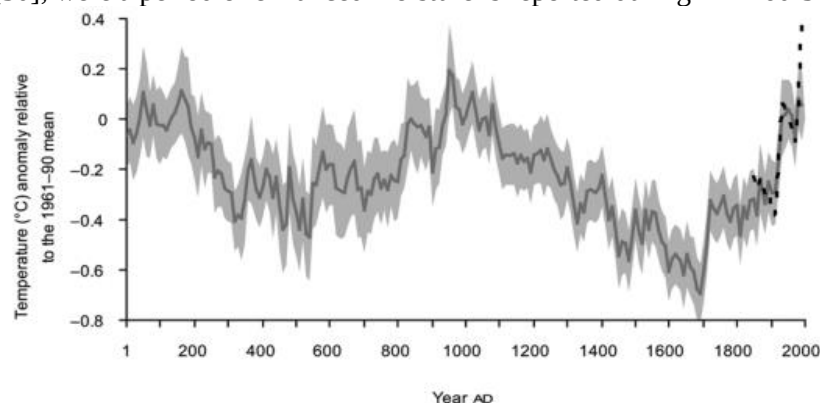


Figure 6. Estimations of extra-tropical Northern Hemisphere (90-30°N) decadal mean temperature variations (dark grey line) AD 1-1999 relative to the 1961-1990 mean instrumental temperature from the variance adjusted CRUTEM3+HadSST2 90-30°N record (black dotted line showing decadal mean values AD 1850-1999) with 2 standard deviation error bars (light grey). (From Ljungqvist [20])

5. Thermal comfort

The thermal comfort index PPD (Predicted Percentage Dissatisfied) is the percentage that quantifies the expected dissatisfied people in a given thermal environment. It has been calculated by Fanger's method

[31] taking into account quantitative values such as: metabolic rate (equal to 1 met=58.2 W/m², corresponding to the energy produced per m² by an average person while at rest. The surface area of an average person is 1.8 m²), Clothing insulation (clothes have a substantial impact on thermal comfort. In order to consider that clothing changes during the year, this value has been adjusted daily from 1 Clo=0.155 m²·K/W down to 0.5 Clo, linearly dependent on the average outdoor temperature. These values correspond to linen tunic and woolen surcoats and knee-length and short-sleeved linen tunic to replicate winter and summer indoor clothing), the Rate of mechanical work (0 W in order to simulate *triclinium* activity), and air velocity (<0.1 m/s, representative of indoor conditions without any mechanical ventilation by embrasures such as windows, vents or significant air leakages).

5.1. Estimation of clothing insulation with regards to 3rd century AD Roman fashion

The value of the clothing insulation as worn by occupants plays a key role in predicting the human thermal comfort [31]. In despite of that, the most common standard of calculation [32,33] only provide limited contexts of application because they are dealing with Western-style clothing ensemble only [34]. Therefore, a reliable supposition based on what clothing arguably were in use in the considered period and place was done, mainly based on literature sources on Roman fashion [35,36] and considering the ancient climate conditions. More specific information could be assessed through experimental methods, such as the ones carried out to evaluate non-Western clothing.

6. Results

6.1. Dynamic simulation outcomes

As expected, air temperature trend in room 14 (with the radiant floor heating system) is greatly higher than the unheated rooms (figure 9), especially the ones far from room 13 (*praeurnium*). The air temperature of room 14 is ranging from about 29°C in winter to over 50 °C in summer, which is a possible indicator of its usage as *balneus* or *sauna*. The adjacent rooms (12 and 15) are indeed affected by the heating during the whole year, with an average temperature difference of 7°C higher than the other unheated rooms (10 and 12). The heating is no longer affecting the air temperature at more than one room distance.

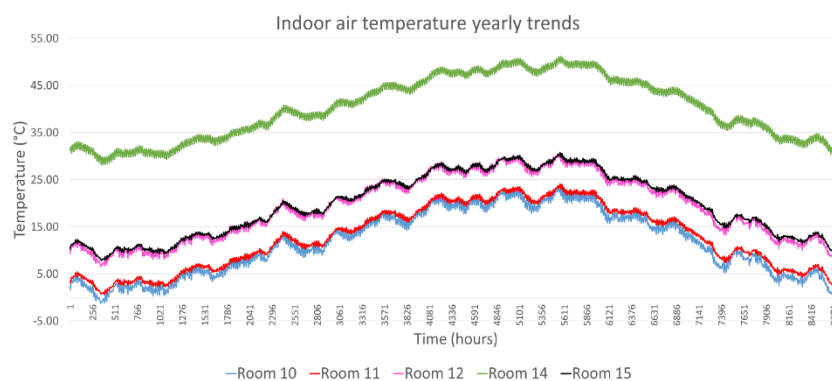


Figure 7. Yearly trends of air temperature inside rooms 10, 11, 12, 14 (heated) and 15.

6.2. Thermal comfort evaluation outcomes

With the exception of room 12 (indirectly heated by rooms 13 and 14), during winter all the rooms are considered very uncomfortable according to modern standards of evaluation. In fact, the average winter values for rooms 6-11 are almost 100% PPD, with minor advantages of rooms 8 and 9. During spring and summer (figure 8) the PPD values of rooms 6-11 are quite low, thus indicating optimal comfort conditions. Moving from room 6 to adjacent rooms 7, 8, 9, 10 and 11 seems to be an improving factor on the perceived thermo-hygrometric comfort, with the optimum in room 11. Room 12 has the best microclimate condition in spring, but during summer it is not comfortable due to the over-heating effect of *sauna* and *praeurnium*. Considering the combined results of the simulations, the most preferable comfort conditions are in room 12 during winter and spring (brown line in figure 8), and in room 11

during summer (black line in figure 8). These results have a very partial correspondence with Vitruvius' suggestions regarding the optimal orientation of the *triclinium* according to the seasons of use, but it should be borne in mind that his experience was linked to the central Italy.

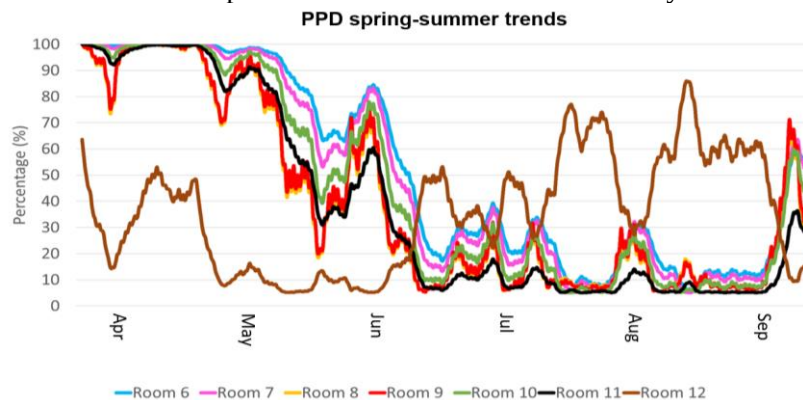


Figure 8. PPD trends during spring-summer period in rooms 6, 7, 8, 9, 10, 11 and 12. The lower PPD values represent the best microclimate in terms of perceived comfort according to modern standard.

Conclusions

Dynamic energy simulation software has been used to investigate an ancient heating system in a 3rd cen. AD building, basing the building model on archaeological hypothesis and direct measurements of the remains. Ancient climate conditions have been considered for energy calculation, and clothing index estimation was necessary to evaluate the comfort conditions. The aim of this work was proposing a new methodology for archaeometry investigation but, regardless of the difficulties in assessing a reliable energy model, this preliminary study allowed to advance more reliable hypothesis on the destination of use of rooms in Roman *domus*, and on the evaluation of the effect of the hypocaust as heating system.

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