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Effect of Wood Properties and Building Construction on Thermal Performance of Radiant Floor Heating Worldwide

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Abstract: Due to its relatively lower thermal conductivity, the suitability of wood is called into question when selecting the flooring material best suited to radiant heating systems. The European standard EN 1264 considers floorings with a thermal resistance over 0.15 m^2 K/W to be out of scope. This belief was partially disproved in a previous article that studied wooden floors for Madrid's climate. However, the effect of climate still needs to be addressed. The present study extends the previous research to worldwide climates and aimed to answer the following questions: (1) Do the lowest thermal conductivity woods present good thermal performance when used in radiant floors? (2) Should the flooring have a maximum thermal resistance value? (3) Is the standard thermal resistance limit of 0.15 m^2 K/W objectively justified? And (4) Do the answers of the preceding questions depend on the climate and the construction characteristics? To answer these questions, 28 cities were selected according to the Köppen–Geiger climate classification. In each city, 216 different dwellings were simulated with 60 wood floorings and one of low thermal resistance as a reference, comprising a total of 368,928 cases. Thermal performance was evaluated in terms of three parameters: energy demand, thermal comfort, and start-up lag time. Consequently, the answers to the previous questions were: (1) The lowest thermal conductivity woods can be used efficiently worldwide in radiant floor heating systems with start-up lag times close to that of the reference flooring; (2) There is no limit value for thermal resistance for floorings that can be applied to all dwellings and climates; (3) No objective justification was found for establishing a thermal resistance limit for flooring of 0.15 m^2 K/W; and (4) Climate and construction characteristics can play an important role in the correct selection of flooring properties, especially in severe winters and dwellings with the greatest outdoor-exposed envelope and the worst insulation.

Keywords: wooden radiant floors worldwide; energy efficiency of buildings; thermal comfort; effect of thermal properties of wood; natural stone vs. wooden radiant floors

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1. Introduction

Radiant heating systems have been in use for thousands of years in many parts of the world [1] due to their advantages over other heating systems, such as high comfort levels [2], high energy efficiency [3], silent operation [2], and compatibility with renewable energies [4–7].

The industrialisation of wood from the nineteenth century onward popularised wood floorings in homes, although in the second half of the last century their market share declined with the emergence of a wider variety of options [8]. Wood nonetheless continues to be one of the most desirable materials for flooring, with annual industry growth rates predicted of around 4.5% [9]. It is commonly believed to be largely unsuitable for radiant floor heating, however, in part due to its thermal conductivity, which is lower than that of ceramic tiles or natural stone. This belief is supported by the maximum thermal resistance value for floor coverings, established as 0.15 m^2 K/W by the European standard EN 1264 [10] in the calculation of radiant heat floors. This figure has been taken to be a hard-and-fast maximum and to mean that floorings with a higher thermal resistance are unsuitable for radiant systems.

To improve the thermal performance of radiant floors, several research studies have focused on construction types [11–14] and control-related factors [13,15–21] such as response time [15] and the inclusion of phase change materials [22–25]. Specifically, some authors have studied the effect of the thermal conductivity of wood on radiant floor heating systems [26] and ways to improve its performance, focusing on reducing the thermal resistance between the water pipes and interior space by means of different installation methods [27] or by improving the thermal conductivity of the floor covering itself [28]. Seo et al. [27] experimentally compared two methods for installing wooden radiant flooring: a floating installation method for laminate flooring and an adhesive installation one for engineered flooring, the former presenting higher thermal resistance than the latter. The test was performed in an actual home in Seoul, Republic of Korea, and the results showed no considerable difference in thermal transfer performance between the two radiant wooden floor heating systems. The same authors [26], in an experimental analysis under laboratory conditions of four types of wood flooring based on heating start-up and shutdown cycles, reported that wood flooring maintained a high temperature for longer periods once the heating source was removed. Similar results were found in the previous study by the present authors [29], where they analysed the thermal performance of 60 radiant wooden floors for the climate of Madrid and 216 dwellings. In many situations, wooden flooring with high thermal resistance was found to deliver higher comfort levels at a slightly lower energy demand than granite floors.

The previous studies were conducted under the premise that it is convenient to reduce the response time and/or improve the heat transfer from the tubes to the surface of radiant floors. However, they do not address the question of whether such improvements are necessary or of significant effect. To answer these questions, it is necessary to study of the radiant floor heating in a way that is coupled with the building, and the building with the climate.

To the authors' knowledge, no studies have jointly analysed the properties of wooden flooring, building characteristics, and climate. Some similar studies have been conducted, namely by Sattari and Farhanieh [30], with a parametric analysis of radiant floor heating installed under conditions comparable to system start-up, and by Alessio et al. [16], who explored the dynamics of three radiant flooring systems in a building with three degrees of insulation and three types of structures. Climate was not addressed as a variable to be analysed by either group, however. The lack of such research prompted the present authors to include climate as an element to be considered in this study, as it may affect the choice of the most suitable properties for any given radiant floor.

This article enlarges the study performed in the previous research by Ruiz-Pardo et al. [29] by extending its scope from dwellings in Madrid, Spain, to include others in 28 cities in which there is a high likelihood of using the heating systems selected according to the Köppen–Geiger classification. The aim was to evaluate the possible effect of the thermal properties of wood, in combination with building characteristics and climate, on the thermal performance of radiant wooden flooring, and to compare it with a highly conductive natural stone floor. This research intends to answer the following questions:

- Are woods with the lowest thermal conductivity efficient for use in radiant floors? The objective is to show whether the lowest conductivity woods can be used in radiant floor heating systems or, conversely, must be rejected based exclusively on that low value. Specifically, this research tried to determine whether woods with lowest thermal conductivity can meet comfort levels requirements with a low energy demand.

- Should the flooring in radiant heating systems have a maximum thermal resistance value for good thermal performance? Is the standard thermal resistance limit of 0.15 m^2 K/W objectively justified?
- Do the answers to the preceding questions depend on the climate and the construction characteristics of the buildings?

To answer the above questions, 216 different dwellings in 28 cities were simulated with 61 radiant heat floorings (60 wood and one of low thermal resistance as a reference), resulting in a total combination of 368,928 cases. The thermal performance of the radiant floor heating systems was evaluated in terms of three parameters: (1) energy demand, (2) indoor thermal comfort, and (3) start-up lag time period.

2. Methodology

The methodology followed in this research is based on simulations of dwellings with a radiant floor heating system. Simulations were performed in a transient state with a time-step of 15 min for the coldest month in each of the 28 cities included. That month was defined as the one having the most heating degree days using a base of 20 °C, this being January for all the cities in the northern hemisphere and July for those in the southern hemisphere. The climate data were taken from Meteonorm [31].

The simulation model used was presented in the article by Ruiz-Pardo [29], which performed a transient coupled simulation of the building and radiant floor heating. The radiant floor heating was modelled with an experimentally validated detailed model based on the response factor method, and the building using a resistance-capacity (RC-network) model. This model is computationally inexpensive with the necessary precision for the purposes of this research, and allows a high number of simulations to be performed in a relatively short time.

As one of the objectives of this research was to study the influence of climate on wooden floors with radiant heating, 28 cities were selected to cover all types of climates from the Köppen–Geiger classification [32] where the use of heating in buildings is expected. A more detailed explanation of the cities selected can be seen in Section 2.1. The total number of simulated dwellings was 216 per city, while 61 radiant heat floorings were considered per dwelling. Additional information about the dwellings and floorings can be found in Sections 2.2 and 2.3, respectively.

2.1. Simulation Types

Two types of simulation were conducted for each dwelling in each city: ‘normal regime’ and ‘start-up lag time’.

The normal regime simulations were performed to determine the energy demand and comfort levels. In this simulation type, the radiant flooring can operate from 08:00 to 23:00 to maintain the indoor temperature at the set-point value of 20 °C, with the constraint that the highest temperature of the upper surface of the floor is 29 °C, as specified in the standard EN 1264 [10]. The energy demand was quantified as the amount of energy supplied on the water side (i.e., supplied by the boiler to heat the water circulating in the pipes) for the coldest month. Indoor thermal comfort, as a subjective parameter, was measured here as the mean number of hours per day that the operative temperature in the space heated was greater than or equal to 20 °C, even in the coldest month (hereinafter ‘comfort hours’), drawn from international standard ISO 7730 [33]. Further to that standard, spaces meeting this minimum wintertime requirement lie under comfort class B, with a PPD (predicted percentage dissatisfied) under 10%.

The start-up lag time simulations were performed to evaluate the time required to raise the indoor temperature to the set-point value of 20 °C with the radiant floor continuously operating based on certain initial conditions depending on the city. The weather conditions for these simulations were those corresponding to the day with the lowest mean outdoor temperature in the coldest month of the year, repeated three times (72 h). The simulation ended after 72 h or when the set-point temperature was reached, if earlier. The initial conditions were previously obtained in each city from a free-floating simulation under the weather conditions prevailing in the coldest month of the year.

The total number of simulations performed was the number of cases (368,928) multiplied by the two simulation types, yielding a value of 737,856 simulations. As the mean time per simulation was around 5 s using an Intel® Xeon® processor (CPU E5-1620 V3 @ 3.50 GHz; 16.0 GB RAM), the total computational time was 1025 h. To reduce the real simulation time, two computers were used working in parallel, making a total of 8 parallel execution processes, achieving a total real time of approximately 128 h (5 days and 8 h).

2.2. Selected Cities for Simulations

A total of 28 cities were selected to study the effect of climate on the thermal performance of wood radiant floor heating. The 28 cities were chosen to cover all the Köppen–Geiger classification climates where residential heating would be expected to be required. The cities chosen are located on the map in Figure 1.

	City	Köppen class.
1	Anchorage	Dsc
2	Beijing	Dwa
3	Berlin	Dfb
4	Budapest	Dfa
5	Chengdu	Cwa
6	Irkutsk	Dwc
7	Istanbul	Csa
8	Kabul	Dsa
9	Krasnoyarsk	Dfc
10	Kwangju	Dfa
11	La Paz	ET
12	London	Cfb
13	Madrid	BSk
14	Moscow	Dfb
15	New York	Dfa
16	Ottawa	Dfb
17	Paris	Cfb
18	Rome	Csa
19	Seoul	Dwa
20	Shanghai	Cfa
21	Teheran	BSk
22	Tokyo	Cfa
23	Torshavn	Cfc
24	Ushuaia	ET
25	Vancouver	Csb
26	Vladivostok	Dwb
27	Yakutsk	Dfd
28	Yozgat	Dsb

Figure 1. Cities selected to study the effect of climate on thermal performance of radiant wooden floor heating.

The criteria used for selecting the cities were the following: (1) For each climate of the Köppen–Geiger classification, a search was performed for cities with a large population; (2) For climates in which there were several cities with a large population, more than one was selected to obtain more information on climate zones that are particularly significant, due to the number of inhabitants; and (3) Geographically distant cities, preferably from different continents, were selected to achieve a good worldwide geographical representation. As an example, it can be observed that three cities were selected for the "Dfa" climate: Budapest (1.7 million inhabitants, Hungary, Europe), Kwangju (1.5 million inhabitants, Korea, Asia) and New York (8.4 million inhabitants, USA, North America), given that they are three highly populated and geographically distant cities. In some cases, nearby cities were selected for the same classification, as is the case of the "Cfb" climate in which London and Paris were selected due to their large populations and therefore the high degree of representativeness of these two cities. Finally, a concentration of cities can be observed in the eastern part of Asia and in Europe, which is a consequence of the combination in these two regions of highly populated cities requiring heating in winter and the high climate variability in a relatively small geographical area.

2.3. Simulated Dwellings

A total of 216 different dwellings in each city were simulated, these being the same as in the previous article by Ruiz-Pardo [29], with the difference of including the overall heat transfer coefficient (U-value) of the outer enclosures, since in the previous article these values were approximated for Madrid. In the present study, because different climates are considered, appropriate U-values must be selected for each one. A brief description of the main characteristics of the simulated buildings can be found in Appendix A.

The guidelines regulating the U-values of building envelopes in the different regions of the world are not governed by a universally accepted procedure, nor using exclusively technical reasons. This results in there being no single rule applicable to all regions of the world regarding the climate and the levels of insulation of buildings. Inasmuch as each country sets its own insulation requirements, the reference U-values for relatively similar climates may vary widely, as Table 1 shows. On the other hand, real buildings in different parts of the world do not strictly comply with current regulations, either because they were built before they came into force, or because their designers have wanted to exceed what is established by the regulations. This results in existing buildings all around the world presenting a wide range of insulation levels. Nevertheless, generally speaking, the colder the climate, the lower the U-value of the building envelope is expected to be. Thus, it is clear that to obtain consistent results, it is not possible to use the normative U-values in each legislation. For this reason, the U-value of the envelope was defined for each dwelling in each city on the grounds of the following:

- Insulation was assumed to be consistent with the type of climate. This led us to define a simple relationship or law between the U-value of the building envelope and the climate of each city. This was merely intended to establish a logical and simple evolution between the U-value and the climate conditions to obtain coherent results. For the definition of said law, the normative values existing in a large number of countries were taken into account in such a way that although the values used in this study do not necessarily coincide with those required in each place, they are based on them.
- Three building types corresponding to levels of insulation—high, intermediate, or low—were simulated per climate. As a consequence of the definition of a law for the U-value that is applicable to this article, the results and conclusions may be expected to be framed only within a theoretical scope, without any relation to reality. To avoid this, three levels of insulation were established for each location so that, in all cases, the actual insulation values were within the proposed insulation limits. In other words, it is possible that in some cases the regulations of a certain city require a much lower U-value than other legislations for similar climates. In those cases, the established law that defines highly insulated buildings will generate a U-value that satisfies the required normative U-values. Similarly, the law that defines poorly insulated cases guarantees that, for a city in which a higher U-value is required than that which would be required by other legislations for similar climates, the generated U-value is close to that in the regulations in that place. On the other hand, in each city, there are both real buildings that exceed the requirements of current regulations and others that do not comply with them, due to their age or other reasons. In any case, establishing a law that limits the U-values in each city between an upper and lower limit based on the regulations of each region will probably include most of the existing buildings in each of the studied cities.
- Since the insulation was assumed to be consistent with the type of climate, a poorly insulated building in a very cold climate was deemed to be better insulated than a poorly insulated building in a climate with milder winters.
- The reference values assigned to the three levels of building insulation in each climate were drawn from the existing legislation in the different areas (see Table 1).

Table 1. Some of the cities studied, Köppen–Geiger classification, and U-values for representative construction elements.

Country	Area	Köppen–Geiger Class	DD_{CM}	U-Value (Walls)	U-Value (Roof)	U-Value (Windows)	Ref.
			°C	W/(m^2 K)	W/(m^2 K)	W/(m^2 K)	
Italy	Lazio (Rome)	Csa	372	0.50	0.46		[34]
Japan	Kanto (Tokyo)	Cfa	423	0.53	0.37	4.65	[35]
Turkey	Istanbul	Csa	444	0.60	0.40	2.40	[36]
Spain	Madrid	BSk	452	0.66	0.38	3.00	[37]
United Kingdom	London	Cfb	467	0.28	0.16	1.6	[38]
Canada	British Columbia (Vancouver)	Csb	526	0.36	0.21	1.70	[39]
France	Ile-de-France (Paris)	Cfb	532	0.36	0.20		[34]
South Korea	Kwangju-jikhalsi	Dfa	617	0.45	0.25	1.80	[40]
Germany	Berlin	Dfb	625	0.30	0.20		[34]
Turkey	Yozgat	Dsb	671	0.40	0.25	2.40	[36]
United States	New York	Dfa	674	0.46	0.15	1.81	[41]
Hungary	Budapest	Dfa	675	0.45	0.25	1.80	[34]
South Korea	Seoul-jikhalsi	Dwa	722	0.47	0.29	3.84	[40]
United States	Alaska (Anchorage)	Dsc	895	0.32	0.16	1.81	[41]
Canada	Ontario (Ottawa)	Dfb	954	0.32	0.20	1.70	[39]

The established law for the assignment of U-values was based on the degree days of the coldest month of each city. The general outcome was that existing buildings were the least insulated, while the highly insulated ones presented values above the minimum legal requirements. The decision was taken to establish a simple, climate-consistent rule to determine the three levels of insulation in each city since wall and roof thermal resistance (1/U-value) would vary linearly with the degree days in the coldest month in that city, as shown in Equation (1). The relationship obtained by establishing linearity between degree days and thermal resistance was obviously inverse with the U-values, as depicted in Equation (1) and Figure 2.

$$\frac{1}{U} = k \cdot DD_{CM} \quad (1)$$

where U is the U-value of the walls or roof, k a constant whose value depends on the type of element and insulation level (Table 2), and DD_{CM} the heating degree-days using a base of 20 °C in the coldest month in each city.

Table 2. Values for the constant k of Equation (1).

Values in (m^2/W)	Poorly Insulated Building	Intermediately Insulated Building	Highly Insulated Building
Walls	0.0028	0.0042	0.0075
Roof	0.0047	0.0072	0.0138

In Figure 2, the triangular and rhomboid data points are the values listed in Table 1 further to the applicable legislation in each city, and the dotted lines are the values calculated with Equation (1) for the three degrees of insulation entered in the model for the simulations. The lower line plots the values for highly-insulated dwelling, the middle one for intermediately-insulated ones, and the upper line corresponds with poorly insulated dwellings.

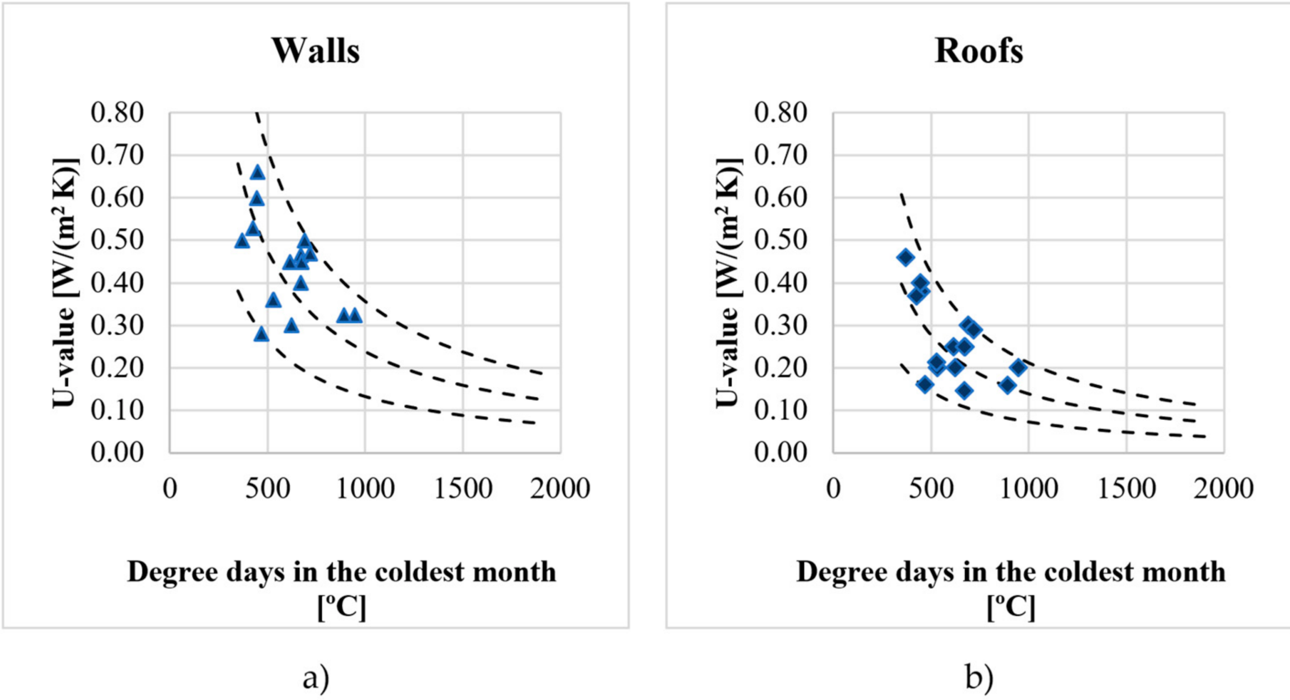

Figure 2. Law for the assignment of U-values with heating degree days in the coldest month in each city: (**a**) walls, (**b**) roof.

Analogous guidelines were used for windows, choosing three types of glazing with the properties listed in Table 3.

Table 3. Window properties selected [42].

	Description	U [W/(m^2 K)]	SHGF
1	Single, 6 mm glazing 20% metallic frame with no thermal break.	5.7	0.72
2	Double glazing, 6 mm panes, 15 mm air space and 20% metallic frame with thermal break; d > 12 mm.	2.8	0.63
3	Double window with low emissivity double glazing, >10 mm spacing between panes and 20% metallic frame with thermal break.	1.6	0.49

Figure 3 shows each glazing type plotted against degree days in the coldest month. The data points are the values listed in Table 1, further to the applicable legislation in each city, and the dotted lines are the values entered in the model for the three degrees of insulation defined for the dwellings: high, intermediate, and poor.

2.4. Simulated Radiant Heating Floors

A total of 61 radiant floors were simulated for each dwelling, these being the same as in the previous article by Ruiz-Pardo [29]. The description of the simulated floors is provided in Appendix B. They consist of a radiant floor configuration with different floorings, 60 of wood and one of granite, which is used as a reference since it has a much higher thermal conductivity than wood. The purpose was to test a wide variety of possible properties of wood floorings used in radiant heating systems to compare their results with a low thermal resistance granite floor covering.

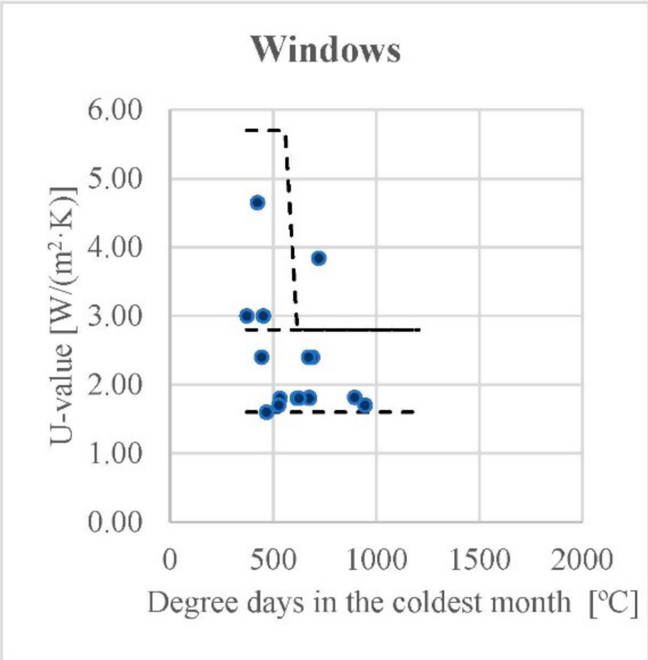

Figure 3. Law for the assignment of window U-values with heating degree days in the coldest month in each city.

3. Simulation Results and Discussion

The performance parameters analysed were those previously described, namely energy demand, indoor thermal comfort, and start-up lag time. The data gathered from 737,856 simulations are so vast that the following analysis and discussion of results is based on averaged values according to climate or dwelling. To answer the questions posed in the Introduction, this section is structured as follows: first, Section 3.1 compares the overall performance results for each city; second, in Section 3.2, five representative cities were selected to show results in more detail depending on the construction characteristics of the dwelling; third, Section 3.3 explores the effect of the thermal properties of wood on the three performance parameters to show whether the lowest conductivity woods should be discarded or not; next, Section 3.4 evaluates the global thermal performance of wood as a construction solution depending on the climate and dwelling construction characteristics. The combined influence of the thermal conductivity and thickness of wood floorings in radiant heating systems (i.e., thermal resistance) is shown for five representative cities. The intention here was to show whether a thermal resistance limit should be established depending on the climate and construction characteristics of the dwelling, and therefore if the established limit of 0.15 m^2 K/W is justified.

3.1. Overall Results

The first findings discussed are each city's overall mean values for the three thermal performance parameters studied, comparing wooden and granite radiant flooring. In the three figures included in this section, the value given for the wooden flooring in each city is the mean value found by simulating the thermal behaviour of the 60 wood floors in each of the 216 dwellings defined. As only one granite floor was defined, the value shown for each city is the mean value of the 216 dwellings analysed. The mean minimum and maximum values for the wood floors in all the 216 dwellings are depicted as error bars.

Mean energy demand values are shown in Figure 4 by city. In this chart, the values were computed excluding cases where the operative temperature was, on average, greater or equal to 20 °C for less than 14 h a day. That criterion was adopted for reasons of comparability since very thick, low thermal conductivity wooden floors, for instance, might present a low heat transfer rate on the water side, from which it might be falsely inferred that they constitute a good choice of material. A low energy demand value under such conditions may be an indication, however, that those floors, able to transfer only small amounts of heat, fail to comply with this minimum comfort requirement of 14 h a day. In short, this figure compares the overall results in terms of energy demand for cases complying with a minimum comfort requirement.

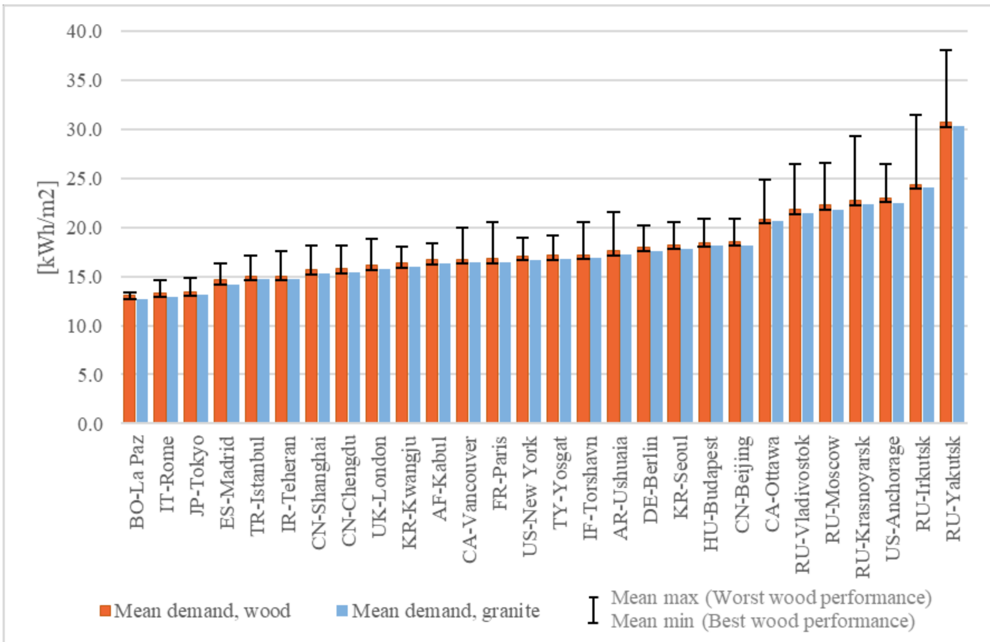

Figure 4. Mean energy demand values in each city.

The mean energy demand for the wooden floors was only slightly higher than that of the granite floor in all the cities, and in nearly every case the mean minimum values associated with the best performing wooden floors (with lowest energy demand) were practically the same as for granite. The mean maximum values, i.e., the mean for the worst performing wooden floor (with the highest demand), varied widely from city to city. In general, a greater difference between the mean maximum and mean values was observed where demand was higher, i.e., where winter weather was more severe. That observation would appear to infer that the choice of a given wooden flooring has less impact in cities with mild winters such as Madrid or La Paz.

The mean values for comfort hours are shown in Figure 5, with fewer observed in the cities with the most severe winters. In all the cities, the mean value for the wooden floors was lower than that for the granite floor, although the difference in most cases was fairly small (1 h or less), the exceptions being places with very severe winters such as Irkutsk or Yakutsk. One finding of note was that the mean maximum, denoting the best-performing woods in terms of comfort levels, were consistently slightly higher than the value for the granite floor, with the exception of extreme winters. In other words, the operative temperature was comfortable for slightly longer with the most suitable wooden floor than with the granite one. Another finding was that the difference between the mean maximum and mean minimum values was greater in the cities with the coldest winters. That supports the premise that the choice of a wooden flooring with suitable properties is more important in cities with severe winters than in those with milder temperatures.

The mean start-up lag time values for each city are shown in Figure 6, including only cases where comfortable conditions were attained in less than 72 h. In all the cities, the mean start-up lag time was shorter with granite floors, with only the best-performing wooden floors exhibiting comparable levels. The graph also shows that the difference between the mean maxima and mean minima was greater in the cities with the severest winters, again implying that the choice of wooden floors with suitable properties would be of greater significance in these cities.

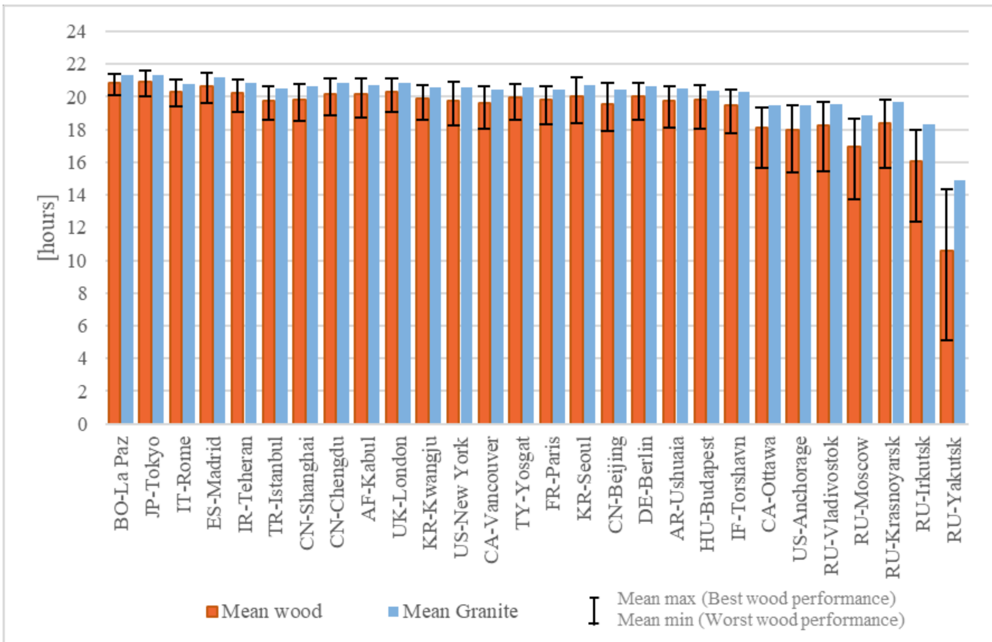

Figure 5. Mean values of comfort hours in each city.

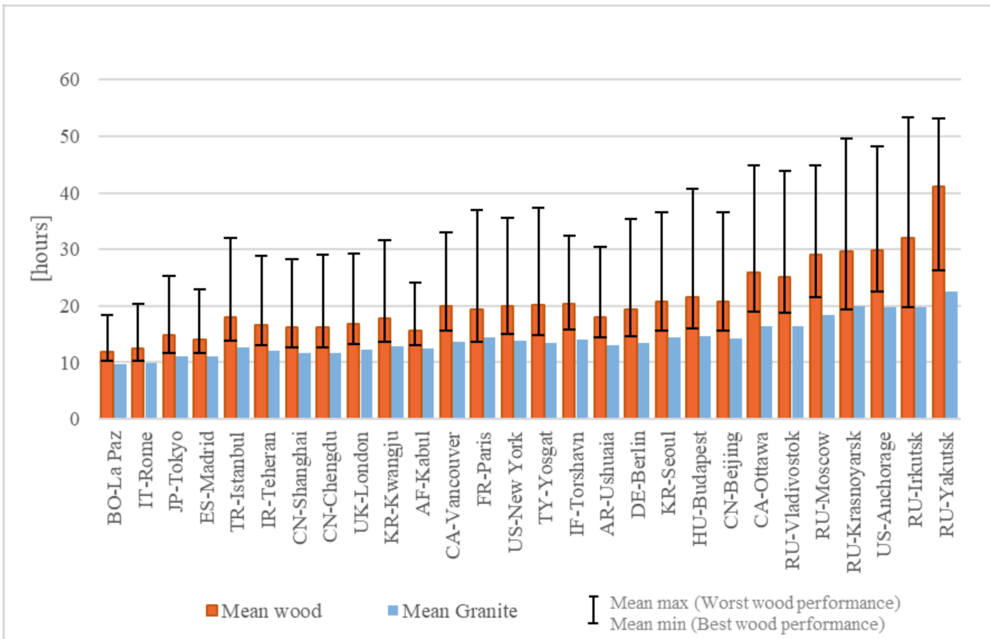

Figure 6. Mean start-up lag times in each city.

3.2. Comparison of Five Representative Cities

Figure 7 shows the performance observed for the three parameters studied in greater detail in five representative cities: La Paz, with the mildest winter; Madrid, with a moderate winter; New York, with an average winter; Moscow, with a severe winter; and Yakutsk, often deemed the coldest city in the world [43,44], with the most severe winter. The figure shows for each city the mean, maximum, and minimum values for each dwelling obtained from the simulation of all 60 wood floors as well as the value found for the granite floor. In each graph, the dwellings are arranged on the x-axis by the mean value for the wood floors. As a rule, interior-located, highly-insulated dwellings are positioned on the left, and corner-located, poorly insulated dwellings on the right, although the dwelling-by-dwelling arrangement varies slightly from one graph to another.

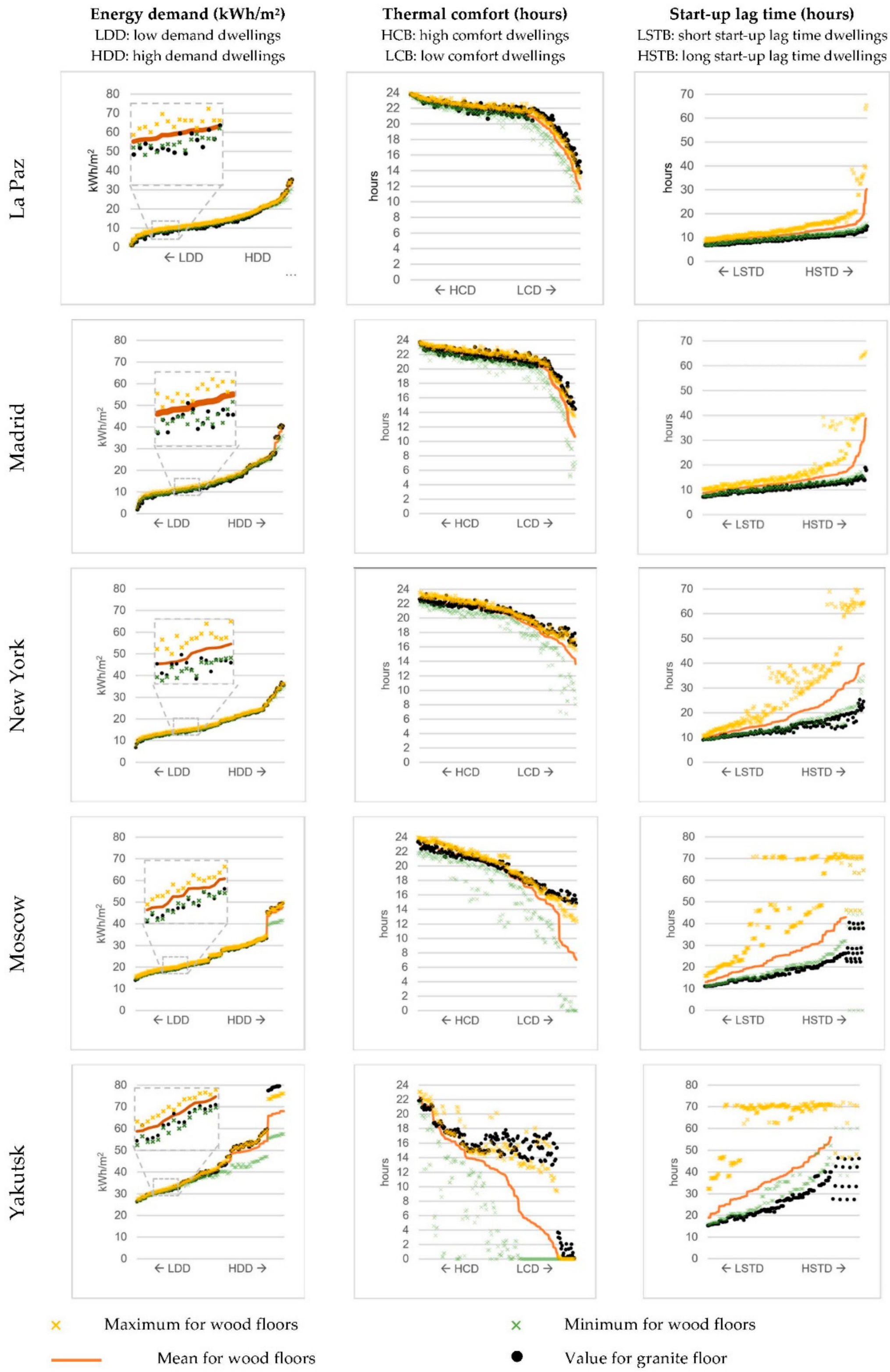

Figure 7. Energy demand, thermal comfort, and start-up lag time in the 216 dwellings in each of the five selected representative cities.

The demand graphs for La Paz, Madrid, and New York show that the four values (mean, maximum, and minimum for wooden floors and the granite floor) overlapped in nearly all dwellings. A very detailed and careful observation reveals that the granite floor exhibited slightly lower demand than the mean for the wooden floors, whilst in many dwellings the minimum demand for the wooden floors was slightly lower than that for the granite. In all three cities, the slightly greater differences were found between the wood and granite floors in the dwellings where demand was highest, although, likewise, those differences were small. This is an indication that the properties of the flooring, whether wood or granite, are of minor importance from the demand standpoint in those cities.

In Moscow and Yakutsk, the demand graphs revealed behaviour similar to that described for the other three cities when heating demand was low, but at values of over approximately 35 kWh/m^2 or 40 kWh/m^2, the data points on the curves for minimum demand for wood floors were perceptibly lower than on the curves for maximum and mean demand. At a heating demand of around 35 kWh/m^2 in Moscow and around 55 kWh/m^2 in Yakutsk, the demand curves rose sharply, a finding not observed in the other three cities. That change in slope is explained by the data in Figure 8, where the heating demand and UA-value of the outer enclosure of the dwellings are plotted against dwelling construction in Moscow. In the part of the figure where demand increased sharply, a sudden rise was also observed in the UA-value of the outer enclosures. This was attributable to the change in the glazing percentage, increasing from 15% or 30% to 80%, which would induce the steep rise observed. In cold and extremely cold climates, the substantial heat losses through outer enclosures due to a sharp rise in the UA-value would significantly increase heating demand. The present authors also observed that in dwellings with a high outer UA-value, under the conditioning control strategy defined here, the system came on at the end of the day for just 1 h or less before shutting down until the next day, a practice that contributed to a higher heating demand. Despite the sharp increase in the outer UA-value, a more suitable control strategy could have lowered heating demand considerably. That attests to the importance of implementing suitable strategies, particularly in poorly insulated dwellings with substantial heat losses. In warmer and milder climates, in contrast, increasing outer UA-values and the concomitant increased heat outflow associated with a higher percentage of glazing would be offset by the solar gains induced and explain the absence of any steep increase in heating demand.

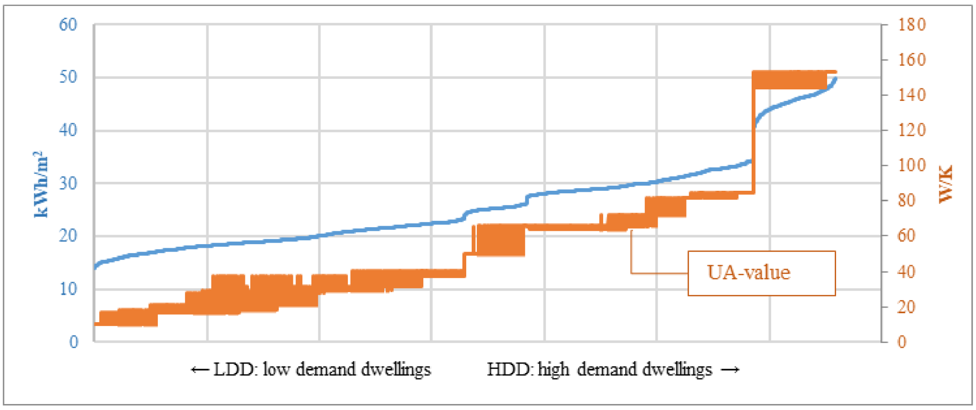

Figure 8. Energy demand and UA-value of outer enclosures for the dwellings of Moscow; in the part of the curve with a sharp increase in demand, around 35 kWh/m^2, a sudden rise of the outer enclosure UA-value occurs due to the increase in the glazing percentage from 15% or 30% to 80%. This change would induce the steep rise observed.

In Yakutsk, at a demand of approximately 60 kWh/m^2, the curves separated, with the highest demand exhibited by the granite floors. The explanation for that unexpected finding lies in that, given its higher thermal conductivity, granite induced a greater heat flow from the water circuit to the indoor space than wood. As a result, as the thermal comfort graph for Yakutsk shows, granite delivered more hours of comfortable conditions than wooden floors, a difference that was more noticeable in dwellings with few comfort hours.

The general observation from these demand curves is that the properties of wooden flooring are of little significance in cases where the monthly heating demand of a dwelling is under approximately 40 kWh/m^2, apparently irrespective of the city involved.

In general, the differences observed in the four values (mean, maximum, and minimum for wooden floors and that for granite floor) in the comfort graph are somewhat greater than the demand graph. In dwellings with the greatest number of comfort hours, largely those where demand was lowest, the values for the wooden floors differed only slightly from those found for the granite floor, and in some cases performed slightly better. As the number of hours at comfortable temperatures declined, the dwelling demand increased, and that difference widened, particularly in the coldest cities. Granite floors exhibited more comfort hours than wood in those dwellings. In short, in dwellings with a greater number of comfort hours, the properties of the flooring in radiant heating systems are of relatively little importance. The choice of wood would have a marginal impact on comfort conditions, and some wooden floorings may be better than granite in this respect. At fewer comfort hours, the flooring properties had a greater impact, with granite performing better than wood, although as a rule wood floors could be found that would deliver comfort levels close to those of granite. More specifically, in mild and moderate climates, the number of comfort hours did not fall sharply as we move to buildings with a greater demand, the difference found being less than 2 or 3 h per day until reaching a point when there was a sharp decrease, typically for corner and badly insulated dwellings with the highest energy demand. In these climate zones, both wooden and granite floors comply with the minimum requirement established here of 14 h per day in practically all the dwellings, with the exception of those with the highest demand, where wooden floors were found to present under 14 comfort hours. Thus, the choice of a wooden floor may be important. In zones with the coldest and most severe climate, there was a steeper decrease in the number of comfort hours in the buildings with a greater demand, although the granite floor complied with the minimum requirement of 14 comfort hours in nearly all the buildings, except in the most severe climate, where it was not able to maintain comfort levels in the dwellings with the highest energy demand. In contrast, only the correct choice of wood flooring would provide a similar number of comfort hours to the granite floor in these climates.

When the start-up lag time was close to 10 h in the dwellings with the lowest demand, the differences between the wooden and granite floors were small. As the lag time lengthened, the gap between the maximum and minimum values for the wooden floors and between those and the granite floor values widened. Nonetheless, some wood floors exhibited lag time values close although not equal to granite.

An overview of the data in Figure 7 shows that:

The properties of the flooring scarcely affect the energy demand in the following cases:

- Dwellings located in climates with moderate or mild winters.
- The vast majority of dwellings in cold climates.
- Low-to-moderate energy demand dwellings in extreme climates.

The properties of the flooring scarcely affect the thermal comfort in the following cases:

- Dwellings located in climates with moderate winters.
- Dwellings with low-to-moderate energy demand in mild winters.
- Dwellings with low energy demand in cold climates.
- No dwellings in extreme climates.

The properties of the flooring scarcely affect the start-up lag time in the following cases:

- Dwellings with low-to-moderate energy demand in moderate winters.
- Low energy demand dwellings in mild climates.
- No dwellings in cold and extreme climates.

Wooden floors may be chosen in these cases on grounds other than thermal properties. In any other case, the appropriate wooden flooring should be chosen to ensure acceptable energy demand, comfort conditions, and start-up lag times.

3.3. Effect of Thermal Conductivity

The preceding section discusses the findings for energy demand, thermal comfort, and start-up lag time depending on climate and dwelling construction characteristics. The mean, maximum, and minimum values for wooden floors were compared with the value for granite. This section addresses the impact of the thermal properties of wood on these three performance parameters. As in the previous research [29], only the thermal conductivities that performed best are shown. The thermal inertia (density, specific heat, and conductivity) of all the radiant floor materials was envisaged in the simulations. However, this section addresses the impact of only the thermal conductivity of the flooring because of the relationship existing between the thermal conductivity and density of wood shown in [29], and because the same specific heat was considered for all the kinds of wood. Therefore, the effect of varying thermal conductivity encompasses the effect of thermal inertia.

No simple rules can be found to define the properties that a wooden flooring must possess to minimise energy demand depending on the dwelling and climate. In pursuit of a possible solution, the wooden floorings were grouped by thermal conductivity and the percentage of cases was determined for which each conductivity range exhibited the best performance.

Figure 9 shows the percentage of cases among all the dwellings and cities analysed in which each thermal conductivity range would be that of choice from an energy demand and thermal comfort perspective. Figure 9a shows the percentage of cases in which each conductivity range was identified with the lowest energy demand while meeting the minimum comfort requirement of 14 h a day. It shows that the percentage was highest in the highest conductivity range, although in 10% of cases the heating demand was lowest for the wood floorings with the lowest conductivity. The percentage of cases of each conductivity range associated with the greatest number of comfort hours is shown in Figure 9b. The wood in the highest conductivity range delivered greatest number of comfort hours in a higher percentage of cases, although that with a thermal conductivity as low as 0.12 W/(m·K) was associated with the highest comfort levels in 10% of the cases.

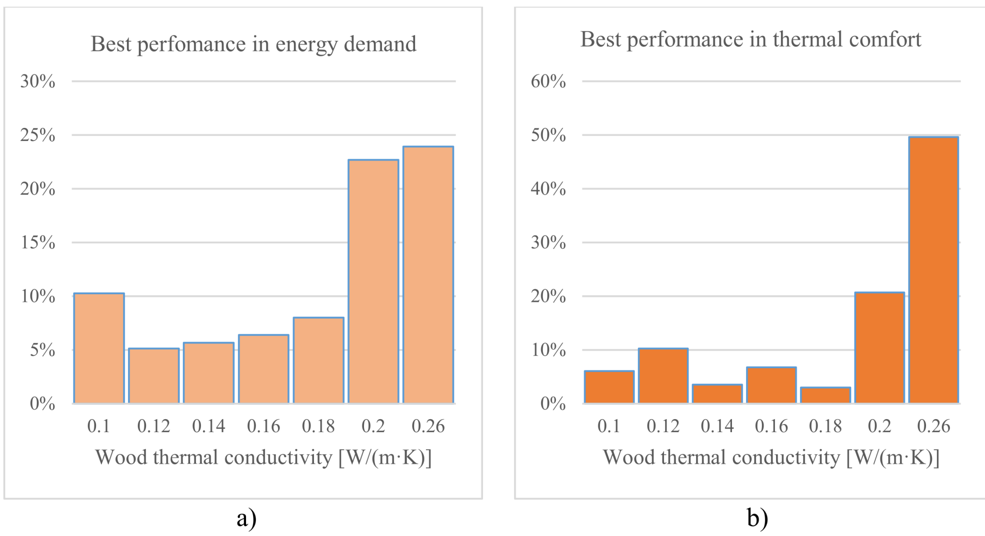

Figure 9. Percentage of cases in which each conductivity range was identified with (**a**) the lowest energy demand while meeting the minimum comfort requirement and (**b**) the greatest number of comfort hours.

This behaviour pattern was also found in the previous research by the present authors [29], in which they analysed the effect of wood properties on energy demand and thermal comfort in Madrid. The present study demonstrates the aptness of low thermal conductivity wooden floorings for providing thermal comfort with low energy demand in dwellings all around the world. A priori, no wood should be rejected for use in radiant floors from an energy demand and comfort point of view solely on the basis of its conductivity value. It is clear that to evaluate the thermal behaviour of these heating systems correctly, it is necessary to perform a simulation of the radiant floor together with the building under transient conditions.

As in the previous research, for all dwellings and in all climates, the radiant floor that consistently presented the shortest lag time to attain the set-point temperature after start-up was the one with the highest thermal conductivity and the least thickness. Nonetheless, the impact of thermal conductivity on variations in this parameter is worth exploring. This is shown in Figure 10, where the reference corresponds to the floor with the highest thermal conductivity. For each thermal conductivity value, it shows the mean, maximum, and minimum percentage increase in start-up lag time relative to the reference value, averaging for all dwellings in all climates. As observed, the mean minimum difference values for all the thermal conductivities was under 10%, whilst the mean differences were under 25% for all the conductivities relative to the reference. In turn, the mean maximum differences compared with the reference were under 40% for all thermal conductivities. This shows that, although greater thermal conductivity results in shorter start-up times, cases exist in which low thermal conductivity does not mean excessive increases in these times. Thus, a wooden flooring should not be rejected solely on the basis of its conductivity value.

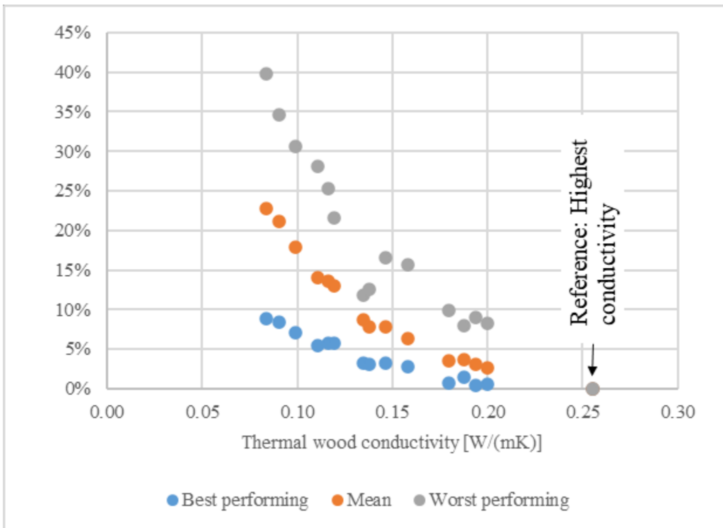

Figure 10. Effect of wood thermal conductivity on start-up lag time: percentage rise of start-up lag time relative to that of the floor with the highest wood covering conductivity.

3.4. Effect of Thermal Resistance

The mean results in the previous section indicate that, a priori, no wood should be rejected for use in radiant flooring based solely on its thermal conductivity value. However, different thermal behaviour should be expected when a certain thickness of a wood is used in a specific climate or building. This section aims to clarify whether certain combinations of wood and thicknesses should be rejected according to the climate and construction characteristics of a dwelling. Specifically, the parameter that relates the thermal conductivity and thickness of a material is thermal resistance, which is one of the most commonly used measures of the thermal performance of construction materials. Thus, this section explores the effect of the thermal resistance of wooden flooring on the thermal performance of radiant heat systems.

Figure 11 shows how the thermal resistance of the wooden flooring affects energy demand, thermal comfort hours, and start-up lag time for the five cities selected in Section 3.2. Three data series are shown: series 1 corresponds to dwellings with the lowest energy demand, greatest comfort hours, or shortest start-up lag time for the respective thermal conductivity values (referred to as 'best performing'); Series 2 corresponds to dwellings with the highest energy demand, lowest comfort hours, or longest start-up lag time for the respective thermal conductivity values (referred to as 'worst performing'); and Series 3 corresponds to the mean values for energy demand, comfort hours, or start-up lag time for the respective thermal conductivities considering all dwellings. Since the designation of 'best' and 'worst performance' in Figure 11 varies depending on the parameter analysed, the best-performing dwellings in terms of comfort were not necessarily the best regarding demand or start-up lag time, although this often was the case. As a rule, the dwellings that performed well in one parameter also exhibited good performance in the other two. The data represented by hollow dots in the figure correspond to cases where the minimum comfort requirement of 14 h a day was not met.

The findings in Figure 11 are addressed parameter by parameter below. Concerning energy demand, the data for the best performing dwellings (Series 1) and also for the mean (Series 3) showed that it was practically unrelated to thermal resistance in all but one city, Yakutsk, where the mean series declined very slightly with rises in resistance. That decline was attributable to the decline in pipe-to-space heat transfer capacity with rising thermal resistance. One consequence of lower heat transfer was fewer hours in conditions of comfort; on average, at a thermal resistance above around 0.10 m^2 K/W in Yakutsk, the radiant system failed to meet the minimum comfort requirement of 14 h a day. For the worst-performing dwellings (Series 2), the energy demand fell at higher thermal resistance values for all the cities, although this decrease was more significant in the coldest climates. As explained above, that decline was attributable to lower pipe-to-space heat transfer, resulting in fewer comfort hours. In all the cities, the radiant system failed to meet the minimum comfort conditions after exceeding a given thermal resistance. Specifically, the worst performing dwellings in Yakutsk failed to reach these minimum conditions at any thermal resistance.

In the best-performing dwellings (Series 1), rises in thermal resistance had no effect on the number of thermal comfort hours. In nearly all the cities, such dwellings presented thermal comfort conditions for close to 24 h a day. On average (Series 3), rises in thermal resistance led to a decrease in the number of comfort hours, this decline depending on the severity of the winter in each city. In those with a mild winter (La Paz), the slope was shallow, while it was steep in those with harsher winters (Yakutsk), where the minimum comfort conditions were not met at thermal resistance values greater than 0.10 m^2 K/W. The worst-performing dwellings (Series 2) exhibited behaviour similar to that observed for the mean except that the downward slope was steeper. In Moscow, once a given resistance value was exceeded (around 0.20 m^2 K/W), the number of comfort hours in this group of dwellings dropped to zero, and in Yakutsk the number was zero at all thermal resistance values.

Finally, regarding the start-up lag time, in the case of the best-performing (Series 1) and mean (Series 3) dwellings, greater thermal resistance induced an increase in the number of hours needed to reach the set-point temperature, although the slope varied with winter severity, increases being more substantial in cities with a severe winter climate. In all the cities, the rise in the mean value was steeper for all dwellings than for those with the best thermal performance. Certain anomalies were detected in the mean values in Moscow and Yakutsk, where the number of hours decreased slightly before increasing again. The explanation lies in the fact that the mean value for a given thermal resistance was calculated only for dwellings where the set-point temperature was reached within the first 72 h (limit time period used in the start-up lag time simulations). Since with rising thermal resistance fewer dwellings met that condition, the relative weight of the best performing dwellings rose, causing the mean lag time to decrease slightly with rising thermal resistance. In the worst-performing dwellings (Series 2), rising thermal resistance had a significant impact on the number of hours required to achieve comfortable conditions. Above a certain resistance value, the set-point could not be reached within the 72-h time limit, particularly in the coldest cities. In Moscow and Yakutsk, the set-point was only attained within the specified time in dwellings with the two lowest resistance values, i.e., with the granite floor and with the wood floor with highest thermal conductivity and thinnest wood. The discontinuities observed in this series were explained in detail in Appendix C of the previous research [30]. In these cases, although the radiant floor is in operation, the drop in temperature during the night interrupts the increase in the indoor temperature, resulting in the set-point temperature not being reached until the second or third day, leading to the discontinuities observed.

Overall, in the best-performing dwellings, the thermal resistance of wood played a very minor role in the energy demand and thermal comfort, irrespective of climate. In these dwellings thermal resistance was only found to induce a considerable rise in the number of hours needed to reach the set-point during system start-up in the coldest climates. The data for the mean of all the dwellings may be summarised in similar terms, although the thermal resistance of wood had a greater effect on the three parameters. In the worst-performing dwellings, the greater thermal resistance of wood prompted substantial variations in energy demand, thermal comfort, and start-up lag time, especially in the coldest climates. In view of the results, dwellings can always be found in which a wooden floor with any level of thermal resistance provides similar comfort conditions to granite floors, and with similar energy demands. This is even the case in the coldest climates. Referring to mean values, with the exception of Yakutsk, wood floors always provided the required minimum levels of comfort, with very similar performance to granite. These results suggest that there is no justification for rejecting a flooring on the basis of its thermal resistance value. In any event, if it were necessary to choose a thermal resistance limit, a plausible criterion would be to do so according to the mean behaviour of the dwellings in a specific climate. In this case, Yakutsk, the coldest city in this study, would be the only city where this limit should be established, this value being approximately 0.10 m^2 K/W.

In another vein, since creating comfortable conditions is the primary purpose of heating systems, it was necessary to determine the percentage of cases of all the dwellings included in this analysis where the minimum comfort requirement of 14 h a day was fulfilled for each thermal resistance value in each city. Figure 12 shows this percentage plotted versus thermal resistance for five cities. In La Paz and New York, an increase in thermal resistance led to a minor decline in the percentage of cases meeting the minimum comfort requirement. That was also true for all the cities with winter severity lying between the climates prevailing in La Paz and New York. As observed in the figure, even at the highest resistance, 90% of the dwellings met the comfort requirements. For dwellings in colder climates such as Moscow, a rise in thermal resistance perceptibly lowered the percentage of cases meeting comfort conditions, from approximately 99% for the granite floor to 94% for the wooden floors with the lowest thermal resistance and 66% for the wooden floors with the highest resistance. In the two coldest cities analysed here, Irkutsk and Yakutsk, thermal resistance had a large impact on the percentage of dwellings attaining comfortable conditions. In Yakutsk in particular, granite floors were compliant in 83% of the cases, compared with only 10% with wood floors presenting the highest thermal resistance. As observed, the percentage of dwellings meeting the comfort conditions even at the highest covering thermal resistance is not negligible, including the coldest climates. Therefore, once again, there is no justification for rejecting any thermal resistance value of the wooden flooring.

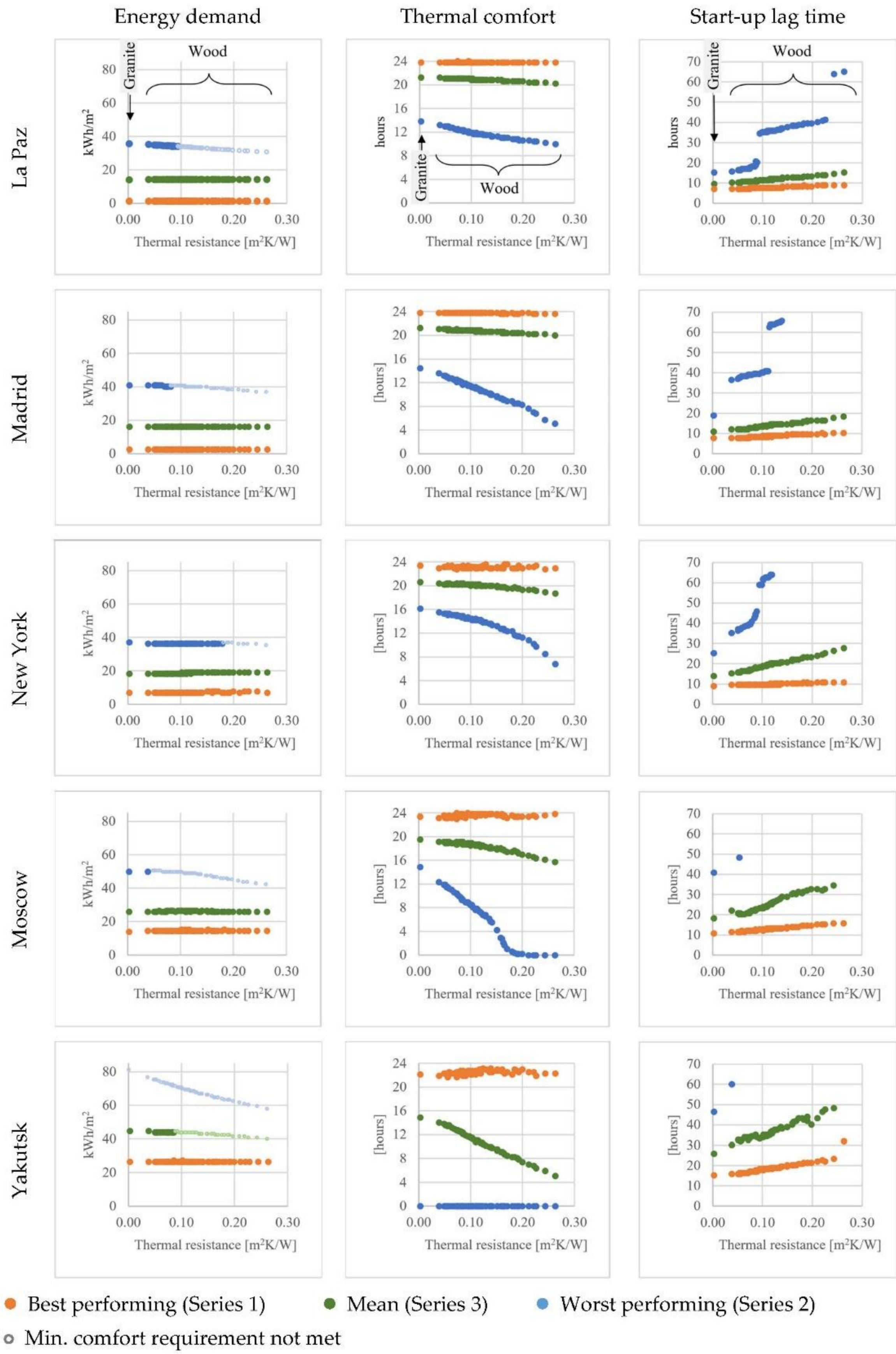

Figure 11. Effect of thermal resistance of wooden flooring on energy demand, thermal comfort, and start-up lag time in five representative cities.

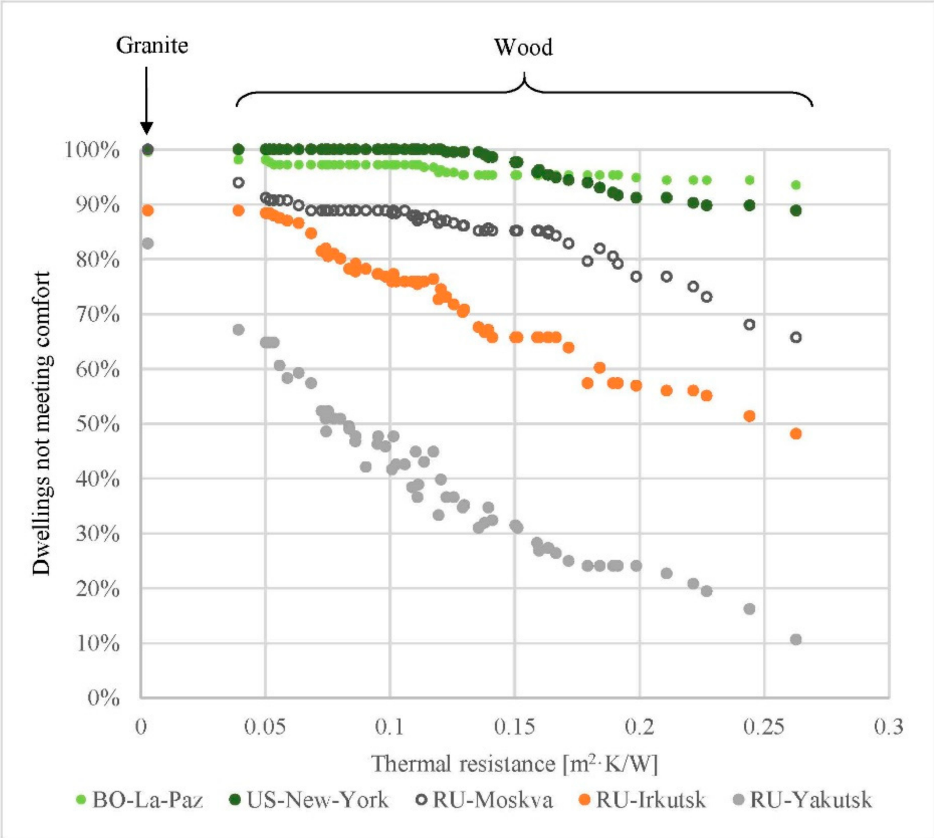

Figure 12. Mean percentage of dwellings meeting the minimum comfort requirement of 14 h a day with top ≥ 20 °C versus thermal resistance of covering for five selected cities.

In summary, probably the most important implications to be drawn from all the results are:

- Wooden floors can perform similarly to granite in the vast majority of buildings and climates, although depending on the climate and the quality of the building, the choice of wood properties will be more relevant. In general terms, it can be said that the more severe the winter and the less insulated the house, the more relevant the proper choice of wood properties. In any case, for most situations it is possible to find a wood that offers performance comparable to that of granite.
- On the other hand, it was found that, although in most cases the appropriate choice of wood is the one with the highest thermal conductivity, this is not always the case, and there are cases in which a performance comparable to or even better than that of granite is achieved with low thermal conductivity wood.

4. Conclusions

The thermal behaviour of 60 radiant wood floors and one granite floor as a reference was simulated in 216 dwellings in 28 cities around the world, selected according to the Köppen–Geiger climate classification, with the aim of answering the questions posed in the introduction of this article. The main conclusions and answers to each of these questions are presented below. A more in-depth analysis supporting the conclusions presented here can be found in Section 3.

- In general, the results showed that in all the climates studied it was possible to find wooden floors with a thermal performance practically identically to granite in terms of energy demand and thermal comfort. One finding of note was that the best-performing woods delivered slightly more thermal comfort hours than the granite floor, with the exception of climates with extreme winters, where it could still be possible to find wooden floors delivering comfort levels close to those of granite. In all the climates,

it was possible to find some wooden floors that exhibited start-up lag times close to those of granite.
- The first question posed was: are the lowest thermal conductivity woods appropriate/suitable for use in radiant floors? According to the findings of Section 3.3, a priori, in terms of energy demand and thermal comfort, the lowest thermal conductivity woods should not be rejected for use in radiant heat floors solely on the basis of their thermal conductivity. The findings showed that wood floorings with low thermal conductivity were able to provide thermal comfort with low energy demand in every part of the world. Specifically, woods with conductivities below 0.18 W/(m·K) presented the lowest demand, complying with comfort in just over 50% of the cases studied, and more specifically, the wood with the lowest conductivity (0.1 W/(m·K)) did so in no less than 10% of the cases. In the same range, namely below 0.18 W/(m·K), the wooden floors provided the highest number of comfort hours in 30% of the cases. Furthermore, based on the results in Section 3.3, there are cases in which the lowest values of thermal conductivity do not lead to excessive increases in the start-up times compared with granite.
- The second and third questions were: should there be a maximum limit of thermal resistance of the flooring in radiant heating systems? And, is the standard thermal resistance limit of 0.15 m^2 K/W objectively justified? In view of the results in Section 3.4, in all climates it was possible to find dwellings in which any value of thermal resistance of the wooden floor provides similar comfort to a granite floor with similar energy demands. This suggests that there are no reasons to set a limit value for thermal resistance that can be universally valid to ensure low energy demand while satisfying comfort conditions. In any case, in the event of having to choose a thermal resistance limit value, a plausible criterion would be for it to be established according to the mean behaviour of the dwellings in a specific climate. In this case, the only city where setting this limit would be necessary is Yakutsk, the coldest city included in this study, and this value would be approximately 0.10 m^2 K/W.
- Finally, the fourth question was: do the answers of the preceding questions depend on the climate and the building construction? The answer is yes. Building characteristics and climate can be important factors when selecting the thermal properties of the floor covering to deliver thermal comfort with low energy demand and reasonable start-up lag times. According to the findings of this research, the choice of a given wooden flooring had little impact in cities with mild winters such as Madrid or La Paz for almost all the dwellings simulated. Similar observations were found for cities with average winters such as New York in terms of energy demand and thermal comfort. However, only in the case of interior-located and better-insulated dwellings were the start-up lag times close to that of granite. In contrast, in severe winters such as Moscow or Yakutsk, the choice of wood covering had a much higher impact on the three performance parameters analysed here. In these climates, comfortable conditions and low energy demand are only possible for interior-located and better-insulated dwellings if the wooden flooring is carefully selected. Regarding start-up lag times, similar values to that of granite can be reached in almost all dwellings if the wooden floor is correctly selected.

This article highlights that the choice of a wood for use in radiant floor systems should not be based solely on its thermal conductivity value; rather, it is necessary to perform a simulation of the system coupled to the building for a specific climate.

Author Contributions: E.Á.R.J.: methodology, software and validation, investigation, data curation, formal analysis, writing—review and editing. Á.R.-P.: methodology, software, investigation, data curation, formal analysis, writing—original draft. M.C.G.: investigation, validation, writing—review and editing. J.A.T.R.: conceptualization, methodology, validation, formal analysis, supervision, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Appendix A

The simulated dwellings are square measuring 9.5 m each side, which results in a surface area of 90.25 m^2. This is a usual area for these types of residential units around the world. The storey height applied was 3 m. Dwellings were assumed to be located in one of two positions: mid-building with just one outer enclosure (hereafter 'interior dwelling'); or on the top floor in a corner location (hereafter 'corner dwelling') (Figure A1).

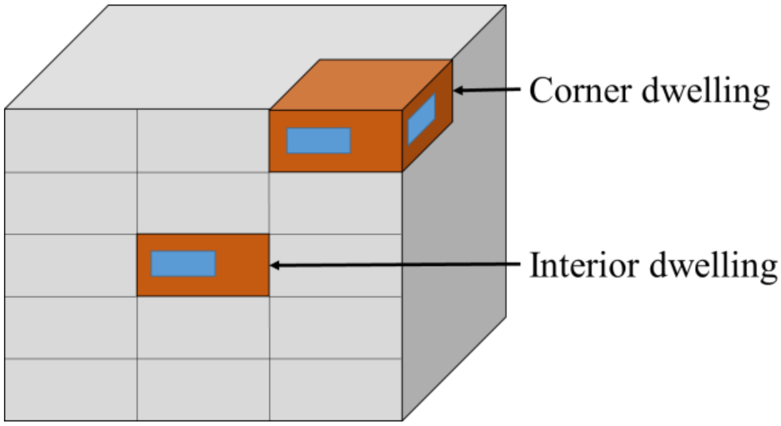

Figure A1. Dwelling locations used in simulations.

In pursuit of a wide variety of construction characteristics, four variables were defined: glazed area, envelope insulation, heat capacity and orientation, summarised below and substantiated in greater detail in Appendix B of the previous article by Ruiz-Pardo [29].

- Glazed area: 15%, 30% or 80%.
- Envelope insulation (U-value) defined by Equation (1).
- Heat capacity: the three levels of heat capacity applied, low, medium and high, were defined as per standard ISO 52016-1:2017 [45].

Table A1. Selected heat capacities for simulations.

Class	Effective Heat Capacity [kJ/(m^2 K)]
Very light	80
Medium	165
Very heavy	370

- Orientation: the four orientations adopted for interior dwellings were north, south, east and west and for corner dwellings southeast, southwest, northeast and northwest.

Consequently, the number of dwellings analysed was the result of combining the above parameters, namely two in-building locations, three percentages of glazing, three insulation levels, three levels of heat capacity and four orientations for a total of 216 in each city.

Appendix B

Radiant floor cases.

Figure A2 shows a schematic layout of the radiant floor used in the simulations.

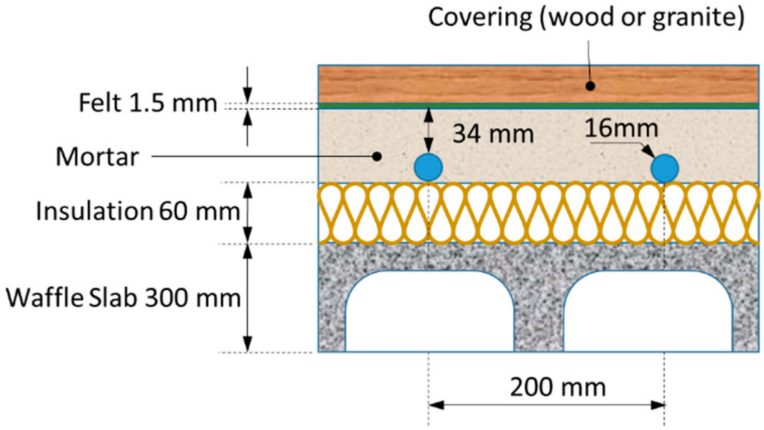

Figure A2. Radiant flooring layout.

The thermal properties of the felt, mortar insulation and waffle slab are shown in Table A2.

Table A2. Thermal properties of materials comprising the radiant floor.

	Thermal Conductivity W/(m·K)	Density kg/m^3	Specific Heat J/(kg·K)
Felt	0.033	90	1000
Mortar	1.8	2100	2000
Insulation	0.033	30	1200
Waffle slab	1.22	1090	1000

The 60 cases of wood floorings considered are the combination of the fifteen thermal properties of the wood shown in Table A3, and four thicknesses (10 mm, 15 mm, 19 mm and 22 mm).

Table A3. Thermal properties of wood used for the simulation. For all cases, the specific heat considered was 1600 J/(kg·K).

	Conductivities for Each Density		
Density kg/m^3	Cond. 1 W/(m·K)	Cond. 2 W/(m·K)	Cond. 3 W/(m·K)
400	0.08	0.11	0.14
500	0.09	0.13	0.18
600	0.10	0.15	0.19
700	0.12	0.16	0.20
850	0.12	0.19	0.26

The material selected for the high thermal conductivity flooring is granite with the following thermal properties: thermal conductivity 3.50 W/(m·K), density 2850 kg/m^3 and specific heat 1.0 kJ/(kg·K). This reference flooring is used for comparison purposes, being flooring number 61.

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