The Ignition Frequency of Structural Fires in Finland 1996-99

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ABSTRACT

In this study the data for the ignition frequency of structural fires was derived from statistics for different building categories in Finland. Following a model obtained from literature, the power law function of the total floor area was observed to be at variance with the data, but working heuristically, it was found that a sum of two power functions led to a fairly good fit with the available statistical data. Since theoretically power law dependence is a special case, a generalized theoretical model was proposed, starting from the initial distributions of the buildings involved in fires and the total stock at risk. Good agreement with the observations was obtained using this ansatz. The general method shed new light on ignition frequency, and good theoretical explanation was achieved for the observed phenomena. It showed that ignition frequency varied with the floor area, and has maxima and minima depending on the form of these size distributions. Estimation of systematic errors yielded values of partial safety constants needed for the calculation of the ignition frequency for design purposes. The model is useful for determining the ignition frequency of buildings with a floor area of between 100 and 20 000 m^2.

KEY WORDS: ignition frequency, risk analysis, fire statistics, building categories

INTRODUCTION

The expected value of the fire loss is the ignition frequency multiplied by the consequences, added up over the distribution of burned buildings from the building stock studied. For different kinds of losses: life, economic, or societal, the frequency is always a linear multiplying factor. Therefore, reliable knowledge of the ignition frequency derived from fire statistics is a prerequisite for quantitative estimation of fire risks. The probability of fire starting is one of the most important factors in fire risk analysis used, for example, in performance based design. Previous studies show [1-4] that ignition frequency is dependent on the floor area of the building. In addition, it has a weak dependency on several other factors, but because of the small amount of data available these factors could not be examined in depth. The purpose of this study was to examine ignition frequency more closely using considerably large amounts of data. This study covered fires in buildings during the years 1996-99, as compared to the years 1994-95 in our earlier study [4]. The data was drawn from the national accident database PRONTO (formerly ONTIKA), which is maintained by the Ministry of the Interior. The information on the building stock was delivered by Statistics Finland.

The definition of ignition in PRONTO is a fire event to which a public fire department has been called. This, however, is by no means a unique definition. Furthermore, we could not be sure of the full coverage of the reports in the database. Some internal checks of the data were made to estimate the influence of these deficiencies on the obtained ignition frequencies.

AVERAGE IGNITION FREQUENCY IN DIFFERENT BUILDING CATEGORIES

The building stock was divided into groups as a function of the floor area according to ten different building categories, which are presented in Table 1. The sizes of these categories were very different. Therefore, it was not possible to carry out all analyses for all categories. Several categories were combined to form new bigger categories where population was sufficient for further analyses.

Table 1 Number of ignitions (1996-99) from the accident database and the combined floor area [m^2] in different building categories according to Statistics Finland.

KEY	MAJOR GROUP	IGNITIONS	FLOOR AREA [m^2]
A	Residential buildings	4 361	231 565 978
C	Commercial buildings	356	18 990 450
D	Office buildings	140	16 354 516
E+L	Transport and fire fighting and rescue service buildings	123	10 627 751
F	Buildings for institutional care	197	8 780 942
G	Assembly buildings	112	7 379 199
H	Educational buildings	122	15 801 759
J	Industrial buildings	1 038	40 321 357
K	Warehouses	405	7 434 710
N	Other buildings	2 650	2 437 960

For rough information on the sizes relative to the number of ignitions during 1996-99, and floor area in different building categories, refer to the data plotted in Fig. 1. It should be noted that almost half of the number of ignitions and 65% of the floor area of buildings fall into residential category A.

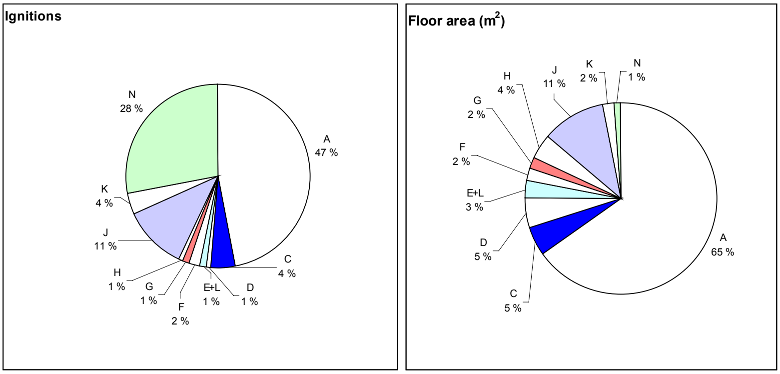

Figure 1 Percentage of ignitions during 1996-99 and floor area in different building categories.

The average ignition frequency [1/m^{2}a], which is the probability per floor area and time unit (annum a) of a building catching fire, was obtained by dividing the number of fires in the specific building category during one year by its combined floor area. The results are presented in Fig. 2.

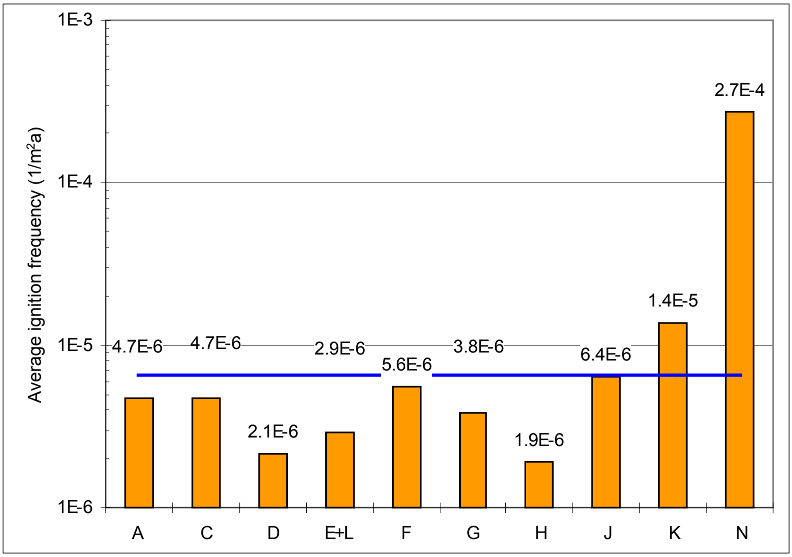

Figure 2 Average ignition frequencies of different building categories during 1996-99. Definitions of symbols are presented in Table 1. The heavy horizontal line represents the average of all categories.

Close to the value of residential category A were categories C, F, G and J. Categories D, E+L and H formed a group, where the values of the ignition frequency were considerably below the mean value 6.6E-6/m^{2}a. The frequencies of categories K and N were both significantly larger than the mean value. A partial explanation for this is that only the buildings which are populated year-round are registered in the Finnish building stock. Thus the data include fires in buildings such as summer cottages, barns or small warehouses, which are registered as fires in the accident database, but their floor area is not registered in the building stock. This problem occurs especially in categories K and N, i.e. warehouses and other buildings. Therefore, the high frequency might mostly be a statistical artifact. However, these categories include a great number of very small buildings, which presumably are poorly controlled and equipped in comparison to bigger buildings. Therefore, there might also be a genuine tendency towards high ignition frequency. Unfortunately, from the data available the question cannot be settled.

DEPENDENCY ON THE FLOOR AREA

The ignition frequency was obtained by dividing the number of fires in the specific category by its combined floor area. The ignition frequency in different building categories as a function of the floor area is represented in Fig. 3 as a general pointer to guide further data reduction. Since the amount of data would be too large, it is not represented in tabular form. **Ignition frequency values from this plot should not be used for any design purposes, since no error bars are shown.** It is presented later in the paper what types of conclusions and what level of reliability can be obtained from Finnish fire statistics at the present level.

The solid line in Fig. 3 is the average ignition frequency of all buildings. There are both differences but also striking similarities in the ignition frequency between different categories, as can be seen from Fig. 3. All of them have high values for small buildings but level off to a much lower value for large buildings. Two of the categories, K and N, deviate strongly from the main body for small floor areas. This behavior is probably caused at least partially, by systematic errors in data gathering, as has already been mentioned above in relation to the averages of the total groups.

Why does ignition frequency of a structural fire change three orders of magnitude when going from the smallest buildings to the largest buildings? The most striking piece of data in Fig. 3 is the behavior for category K (warehouses). We turned to modeling to try to explain the data and also used tools to judge the validity of the data, something which has been criticized by many fire officers in Finland, mainly on anecdotal grounds. The modeling efforts had two goals: (i) Are there general classes of mathematical functions derivable from theory which should be used to fit on data in Fig. 3? (ii) What are the real mechanisms producing area dependent differences in ignition data? We were able to find the answer to question (i), but only got possible explanations in relation to the answer to question (ii).

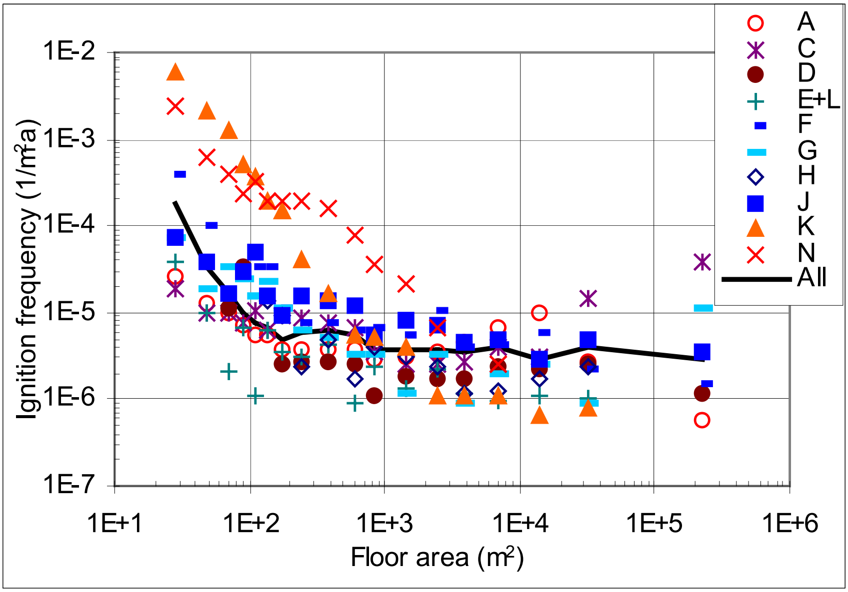

Figure 3 Average ignition frequency 1996-99 of different building categories as a function of the floor area. Definitions of symbols are explained in Table 1.

BARROIS MODELS

Our first attempt [4] was totally experimental, but inspired by a model presented by Ramachandran [1]. Real statistical data from open literature is rare and offered little guidance. By trial and error a sum of two power law functions was fitted to the statistical data. More thorough study of literature after these trials revealed that the function of two power laws is a generalization of a theory proposed by Barrois [7]. The long history of the development is depicted in [4]. Following the proposition by Johansen [8], we call the model family Barrois models, and this particular application the generalized Barrois model. At this phase no theoretical modeling was attempted. Statistical accuracy was still quite low so no attention was paid to minor details. Accordingly, the ignition frequency f''_m was presented in form

$$f''_m = c_1 A^r + c_2 A^s \tag{1}$$

where A is the floor area and c_1, c_2, r and s are coefficients, which were determined experimentally from observations for different building categories. Here the building categories of Table 1 were recombined to form just three groups in order to obtain better statistical accuracy. Groups used were;

1) Residential buildings
2) Industrial buildings and warehouses
3) All buildings except residential and industrial buildings and warehouses

The generalized Barrois model of Equation (1) was fitted to the observations of different groups. The results are plotted in Fig. 4 with values of different parameters. The model worked fairly well in all buildings and industrial buildings as well as warehouses, and would be fully satisfactory for engineering purposes. In residential buildings from Fig. 4 it can be seen that the observations form a clear hump around 10 000 m^2 of the floor area, such that the ignition frequency starts to increase after 2 000 m^2 and decrease again after about 15 000 m^2. The peak was not caused by statistical inaccuracy, and similar peaks were also detected in other groups. Since there were only a few observations in two of the largest floor area classes, based on this data it is not possible to make any conclusions about ignition frequency in buildings with a floor area exceeding 20 000 m^2.

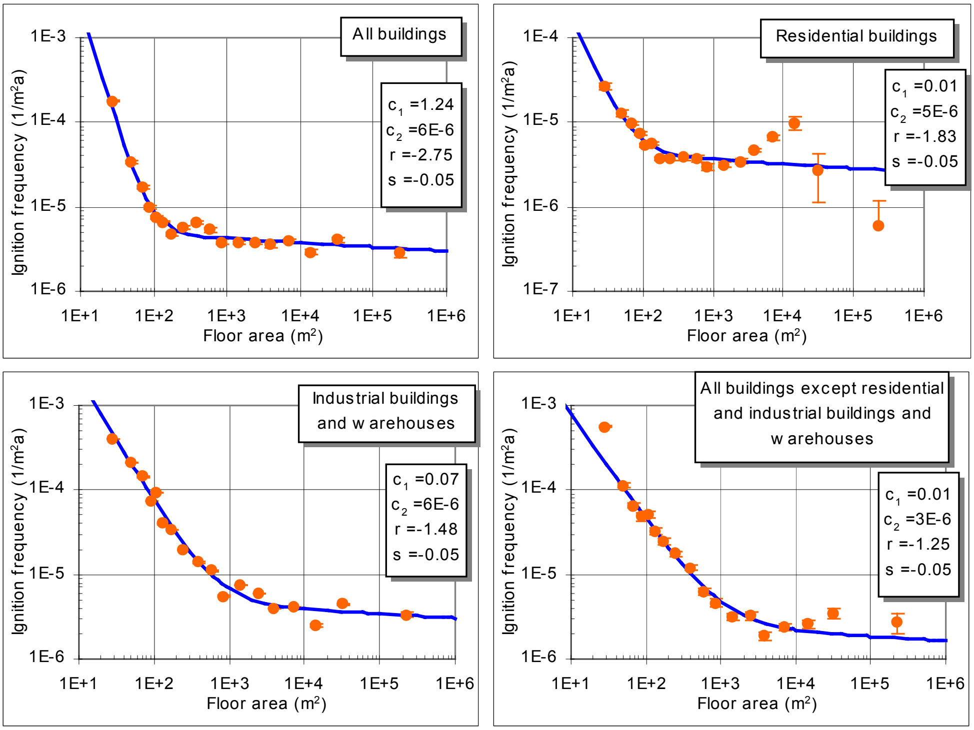

Figure 4 Ignition frequency observations (dots) in different building categories 1996-99 and a generalized Barrois model fitted to the data (solid line). The error bars indicate only statistical noise.

DENSITY DISTRIBUTIONS OF FLOOR AREA

The humps in experimental observations in Fig. 4, especially those for residential buildings above 10 000 m^2 floor area posed questions. Why does it deviate from the generalized Barrois' model? Returning to Ramachandran's theory [1] we noticed that he had derived dependence of fire frequency on the floor area only for two particular types of distributions of building stock and buildings hit by fire. The probability of fire starting in any building depends on the amount and nature of the ignition sources in that particular building. The amount of these sources increases as a function of the floor area such that the ignition frequency is at least, but often primarily the function of the floor area. The probability of fire starting is

$$P(A) = \frac{n}{N}\frac{v_n(A)}{v_N(A)} \tag{2}$$

where n is the number of fires during the time period, N is the number of buildings at risk in the considered area, $v_nA)$ is the number density function of the floor area for buildings involved in fires and $v_N(A)$ the number density function of the floor area for buildings at risk. Ramachandran [1] showed that *P(A)* is a power law, if the distributions of the building at risk and hit by fire are both either Pareto distributions or logarithmically normal distributions with the same standard deviation. It is easy to show that this is not generally true. *P(A)* could have in principle very different forms, depending on the functional form of initial distributions. If they are both normal, *P(A)* becomes an exponential function of A; if they are smooth functions within an interval $A_{min} < A < A_{max}$, *P(A)* becomes constant *n/N* in the whole interval. Therefore it was of interest to generalize Ramachandran's theory and analyze initial distributions $v_n(A)$ and $v_N(A)$ to find which would be mathematically the most likely functional form of *P(A)*.

Examination of the raw data revealed the rationalization for the sum of two power laws, Equation (1), the generalized Barrois model used above, arises from the very nature of the building stock. Residential houses in Finland constitute the great majority of the buildings. They form two natural groups: (a) small houses, starting from a single family house and ending with multiple units in long row houses and (b) apartment houses. Both these subgroups show lognormal floor area distributions with rather different averages. Therefore distribution *P(A)* is dominated by group (a) for lower floor areas, and by group (b) for larger values of floor area. This leads roughly to a sum of two power laws of Equation (1). Closer examination of the data showed that in Finland the density function of the floor area consists of even more subsets. The useful distribution, up to accuracy of visual curve fitting turned out to be a sum of one Pareto and two lognormal distributions

$$v_k(A) = c_{1k}v_{1k}(A) + c_{2k}v_{2k}(A) + c_{3k}v_{3k}(A) \quad , \quad k = n, N \tag{3}$$

where

$$v_{1k}(A) = \lambda_k S_k^{\lambda_k} A^{-\lambda_k - 1} \quad , \quad k = n, N \tag{4}$$

and

$$v_{ik}(A) = \frac{1}{\sqrt{2\pi}\sigma_{ik} A}\exp\left[-\frac{1}{2}\left(\frac{\ln A - \mu_{ik}}{\sigma_{ik}}\right)^2\right] \quad , \quad i = 2,3; \quad k = n, N \tag{5}$$

The values of coefficients c_{ij} are determined such a way that the distributions v_{ij} become normalized. The function (Equation (3)) is plotted in the same figure with statistical observations of residential buildings in Fig. 5.

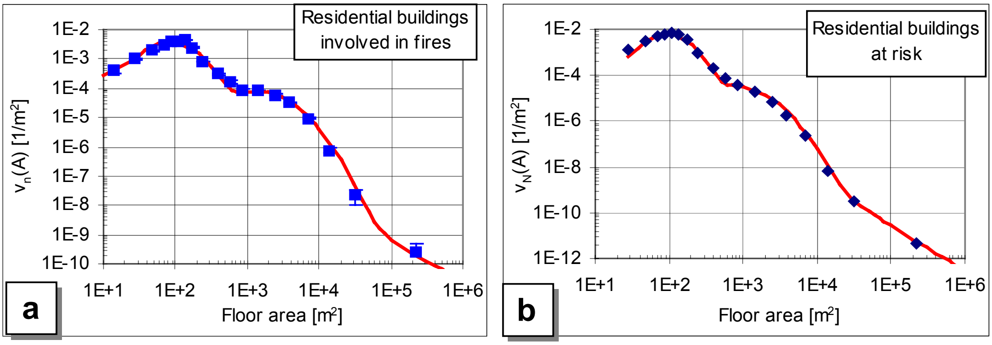

Figure 5 Density function of the floor area for residential buildings. a) buildings involved in fires and b) buildings at risk. Statistical observations are plotted as dots and the theoretical curve (Equation. (3)) as a solid line.

Ignition frequency is the probability of fire starting per floor area. Thus

$$f_m''(A) = \frac{P(A)}{A} \tag{6}$$

where $P(A)$ is obtained from Equation (2). The theoretical ignition frequency in residential buildings calculated using Equations (2)-(6) is represented in Fig. 6 with statistical observations (dots).

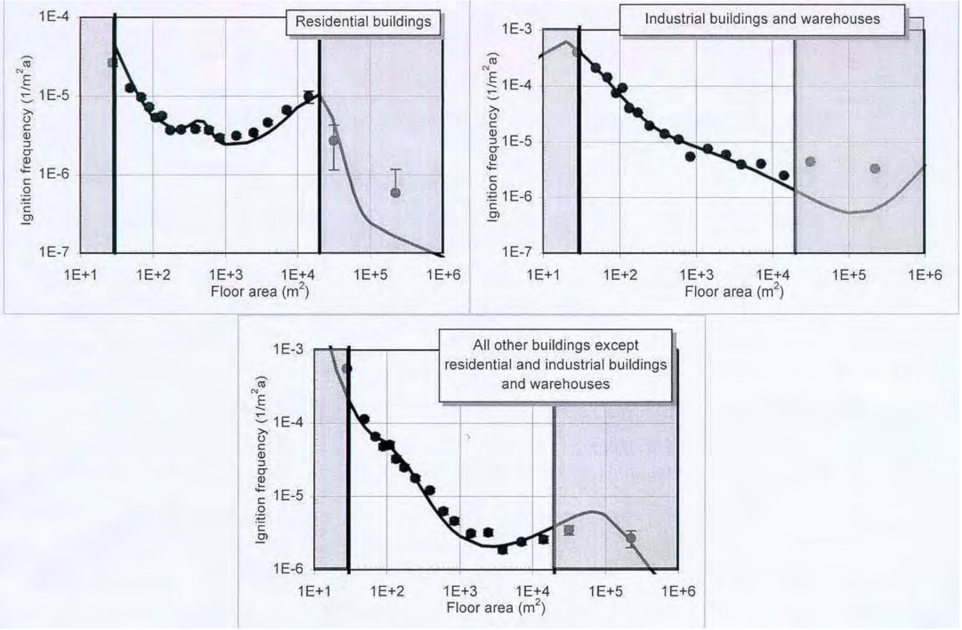

Figure 6 Ignition frequency in different building groups. Statistical observations (dots) and theoretical curve (solid line). In shaded areas there are not enough observations to support reliable estimation of ignition frequency

The theoretical curve in Fig. 6 takes into account the increase of ignition frequency in large values of the floor area, and explains in a natural way the hump in ignition frequency observed at 20 000 m^2 floor area, as well as the smaller hump at 500 m^2. Because of the limitations of the data available statistically significant conclusions about the ignition frequency in very large or small buildings (shaded areas) cannot be made with adequate accuracy. In the area between the heavy vertical lines plotted in Fig. 6 the model is applicable.

This analysis showed that small local ‘peaks’ of ignition frequency are possible and depend on the form of the floor area distributions. In addition, it was noticed that in large values of the floor area ignition frequency does not approach a constant level. However, the used floor area distribution (Equation (3)), which is the sum of three separate distribution functions, is still too simple to describe the actual distributions in great detail.Furthermore, the point of the curve fitting was not to find a fitting which was as accurate as was possible, but to show in general terms why the ignition frequency varies with floor area. Ignoring minor details, the generalized Barrois model (Equation (1)) is still a good simple calculation form proposal for engineering design purposes, provided partial safety coefficients are calculated in such a way that the curve becomes an upper envelope for the observed data points.

Estimates of the effect of systematic errors were made for determination of partial safety coefficients γ_f according to equation:

$$f_s'' = \gamma_f f_m'' \tag{7}$$

where f_m'' is obtained from Equation (6), and f_s'' is the design frequency. It was concluded [9], that for larger buildings (A > 10 000 m^2), f_m'' is overestimated due to systematic errors in building stock. Therefore, a value of γ_f = 1 can be used for design purposes for non-residential buildings. This is in contrast to our earlier rough result [4], where a value of 3 was recommended, with this continuing to be valid for residential buildings.

Why is the ignition frequency in small buildings higher than that in larger buildings? From the trials detailed above we only get pointers, no real data or systematic indications. What do we mean by ignition in this study? Ignition here is taken to mean a fire to which the public fire department is called. It is clear that in larger buildings planned fire safety measures, as well as precautions against fire, are much more stringent than those for small buildings, where generally no special requirements apply. This influences fire ignition frequency and probably has an even greater effect in terms of the ultimate consequences of the fire. There are however, some indicators, the most important of these being the 'packing density'. Ignition needs ignition sources: human activity, equipment faults or natural phenomena. A daily living routine includes a number of deliberate ignitions. A small fraction of these may become uncontrolled. Similarly, certain kinds of equipment have the potential to ignite when energized. The number of these per capita may be fairly constant. In smaller buildings these are 'packed' closer than in bigger buildings. In an uncontrolled environment the failure probability leading to ignition grows as well. These observations suggest possible explanantions but are, at this stage, only ideas which need to be tested in future studies. For these reasons one also has to combine several other statistical data bases other than those used here. Some of these might be readily available, some others may need specific data collection. These types of modelling efforts are worthwhile, because they could lead directly to a better understand of the reasons behind fire ignition. This knowledge is essential in fire prevention work.

TIME DISTRIBUTIONS OF IGNITION FREQUENCIES

The time distributions of fire alarms were plotted for 12, 459 building fires that occurred in Finland between 1996-99. In Fig. 7 the relative time distributions of the alarms is presented in polar coordinates. The periods are: (a) month of the year, (b) day of the week, and (c) hour of the day. The 100% polygons represent mean values.

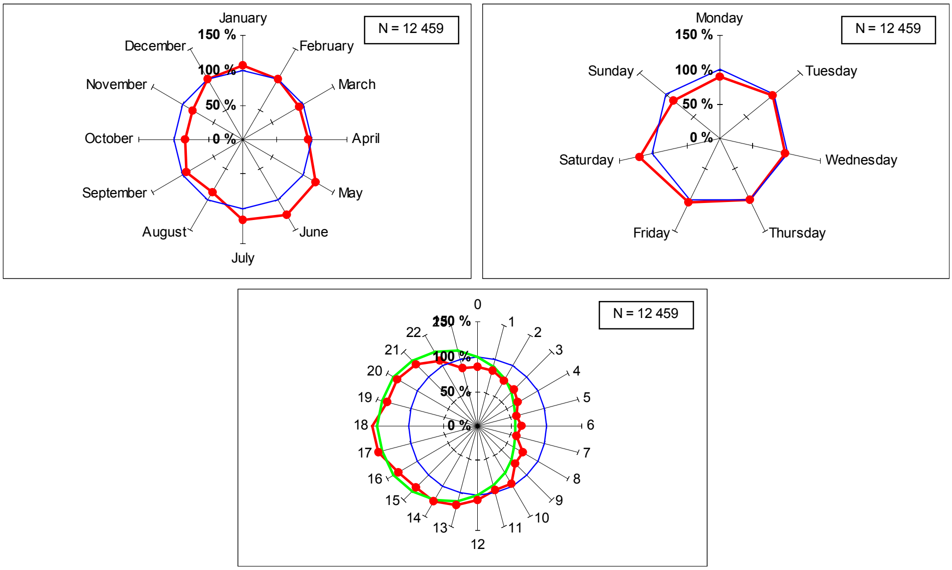

Figure 7 Periodic variation of relative ignition frequencies by month of year, day of week and time of day.

Figure 7 shows that periodic variations are rather small with the exception of the daily cycle. The number of alarms was some 20 to 30% above the average in May, June, and July, but only slightly so in December and January. Using weekly time resolution, ignition frequency increases clearly during the Christmas period and at some other shorter periods, but the curve is so noisy it is not given here. The number of alarms was greatest in June and lowest in November. Weekday variation is even smaller: Friday is 10% and Saturday 30% up, Sunday and Monday some 10% down. Diurnal variation of ignitions has an amplitude of 50%. The lowest value is around 6 a.m., and the peak around 6 p.m., following roughly a sinusoidal cycle on a relative scale

$$f_d(t) = 100 + 45\sin\left[\pi\left(\frac{t}{12} - 1\right)\right] \tag{8}$$

where t is the time, [h]. This is, it would appear, much the rhythm of life of people during waking hours in a residential environment, although we have no specific measured data to show the connection. A very rough conclusion from diurnal variation is that at least a half of the ignitions result directly from human activity. The other half is a combination of human activity (not zero at 6 a.m.!), and other non-human causes. The phase shift of the ignition minimum by 6 hours shows clearly that solar radiation is not a significant component in fire ignitions.

CONCLUSIONS

The ideas put forward by Barrois [7], re-interpreted more recently by Ramachandran [1] and leading to a power law dependence of floor area, was tested using statistical data from Finland. Generalizing it to a sum of two power law functions [4] yielded in the first phase plausible fits on ignition frequency data. While seeking justification for the sum of power laws, Ramachandran's theory was generalized [9] to take into account the real distributions of the building stock and the ignited buildings. It was found that in most cases these distributions could be described as a sum of two lognormal and one Pareto distribution. This generalized theory was able to explain both the sum of two power laws, as well as apparent deviations from it. They were observed in this study, when better statistical accuracy was obtained (as compared to our earlier study [4]). Overall, the mechanism of the factors affecting floor area dependence of the ignition frequency was discovered. As a result, for engineering purposes, statistically reliable ignition frequency graphs for the three building groups were extracted (Fig. 4), on which the design methods can be based. Pointers to future direct modeling of ignition frequencies are given, based on observations gathered in this work.

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SYMBOLS

f_m	Ignition frequency [1/m^{2}a]
A	Floor area [m^2]
c_1	Coefficient of the Barrois model
c_2	Coefficient of the Barrois model
r	Coefficient of the Barrois model
s	Coefficient of the Barrois model
$P(A)$	Probability of fire starting
n	Number of fires
N	Number of buildings at risk
$v_n(A)$	Density function of the floor area for buildings involved in fires [1/m^2]
$v_N(A)$	Density function of the floor area for buildings at risk [1/m^2]
μ	Mean
σ	Standard deviation
λ	Constant of the Pareto distribution
S	Total floor area of the smallest building

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