Title	A Monte Carlo simulation platform of housing fires in Finland forecasting life and property loss
Author(s)	Karhula, Teemu; Sikanen, Topi; Hostikka, Simo; Keski-Rahkonen, Olavi
Citation	Proceedings of the 11th International Probabilistic Safety Assessment and Management Conference and The Annual European Safety and Reliability Conference, PSAM 11 & ESREL 2012. Stochastic Modelling and Simulation Techniques, pp. 08-Mo3, 10 p.
Date	2012
Rights	Reprinted from PSAM 11 & ESREL 2012. Stochastic Modelling and Simulation Techniques. This article may be downloaded for personal use only

A Monte Carlo simulation platform of housing fires in Finland forecasting life and property loss

Karhula, Teemu[a*], Sikanen, Topi[a], Hostikka, Simo[a], Keski-Rahkonen, Olavi[b],
[a]VTT, Espoo, Finland
[b]VTT (retired), Espoo, Finland

Abstract: A new tool is being developed by widening the scope of our earlier platform. In Finland probability of human fire loss has been higher than in most similar countries. The motivation of the development was to estimate effectiveness of potential measures to improve home fire safety. Constructing a bottom-up system synthetically and modeling the dynamics of the key components and agents realistic enough produces a tool for numerical experiments, where causality is built in. This is an advantage over statistical methods, where distinguishing cause from consequence is difficult, and nonlinear, correlating variables cause confusion. Monte Carlo simulations of realistic agents in home fires were carried out piecewise and iteratively to find out the most important variables. Home was the basic unit of Monte Carlo fire simulations carried out in two phases flaming ignition as the borderline. Pre-flaming simulations used statistical data on population, buildings, households as well as time-use and health behavior of people to calculate smoking, drinking, use of relevant medication, and blood alcohol concentration as properties of the agents. A household described by agents was simulated for a single calendar year in time steps of 10 minutes. Parameters were adjusted on diurnal, weekly and yearly cycles. Once an ignition occurred, all data were stored to be used as the input for the second phase. Alarm after ignition, fire protection equipment as well as reactions of agent operands were modeled for Monte Carlo simulations, where fire development in the home was the driving force. Simulations were carried out for life and property loss forecasting. Preliminary results from work still in progress are: (A) active age, (B) elderly, and (C) dependent persons formed three groups of victims, where the path to fatality was different. Smoking and drinking alone in home in group A, memory disorders and physical difficulties in group B are the fatal combinations of risk factors.

Keywords: Life loss, Property loss, Monte Carlo in PSA, Extended use of statistical data.

1. INTRODUCTION

In Finland probability of human fire loss has been higher than in most countries otherwise similar [1]. The motivation of the development was to estimate effectiveness of potential means to improve human fire safety. A Monte Carlo simulation platform of housing fires was drafted (Fig. 1) to forecast life and property loss as well as estimating cost effectiveness of potential measures to improve fire safety. It was started (A1 in Fig. 1) by widening the scope of our earlier platform of carrying out fast Monte Carlo runs [2 - 3]. It could use various fire simulation codes, but FDS [4] only was used here. Online fire data base PRONTO - maintained by the Finnish Ministry of Interior - was our major source of fire related data, which were needed for inputs (A3 in Fig. 1).

Traditional problem approach - top-down analysis of statistical data - has drawbacks: (i) Historical data cannot tell, what will be a consequence of a change in the system. (ii) Analysis can pinpoint important factors, but do not distinguish, what is a cause and what a consequence. (iii) Many of the observed variables are correlated, and their functional dependencies are not know, which hampers analysis of variance models. Therefore, we decided to build a system bottom-up synthetically and to model the dynamics of the key components and operating agents realistic enough to produce a tool for numerical experiments, where causality is automatically built in (B1 in Fig. 1). Monte Carlo simulations were carried out iteratively to find out the most important variables. Initial plans were revised as new information accumulated. Corrections and adjustments were made and converged satisfactorily. In the later phase of the development program large scale simulations produced predictions to compare with historical statistical data where they were available. Using this ‘validated’ platform it was an easy task to modify it for answering the what-if-questions for fire safety policy decisions.

The work is still in progress, but preliminary results are promising. This paper presents the development history and the structure of the platform, as well as results from sub-models. Full scale Monte Carlo simulation data and comparisons will be published later.

2. CALCULATION PLATFORM

2.1. Temporal development

A pilot study included a wide literature search and analysis of all found material on phenomena deemed to be related. No direct example or model for similar tool was found, but important sources for sub-models were located. Fig. 1 details subtask scheme for the Monte Carlo simulation platform. The calculation tool was developed by subunits adding and deleting them as experience accumulated. Dashed line boxes A1 – A4 were included in the pilot study to test the feasibility of the proposed platform. Boxes B1 – B5 were included in the original plan of the main study. Boxes C1 – C4 were added in the midterm revision, and box C4 due to feedback of the first full scale simulations including most subunits.

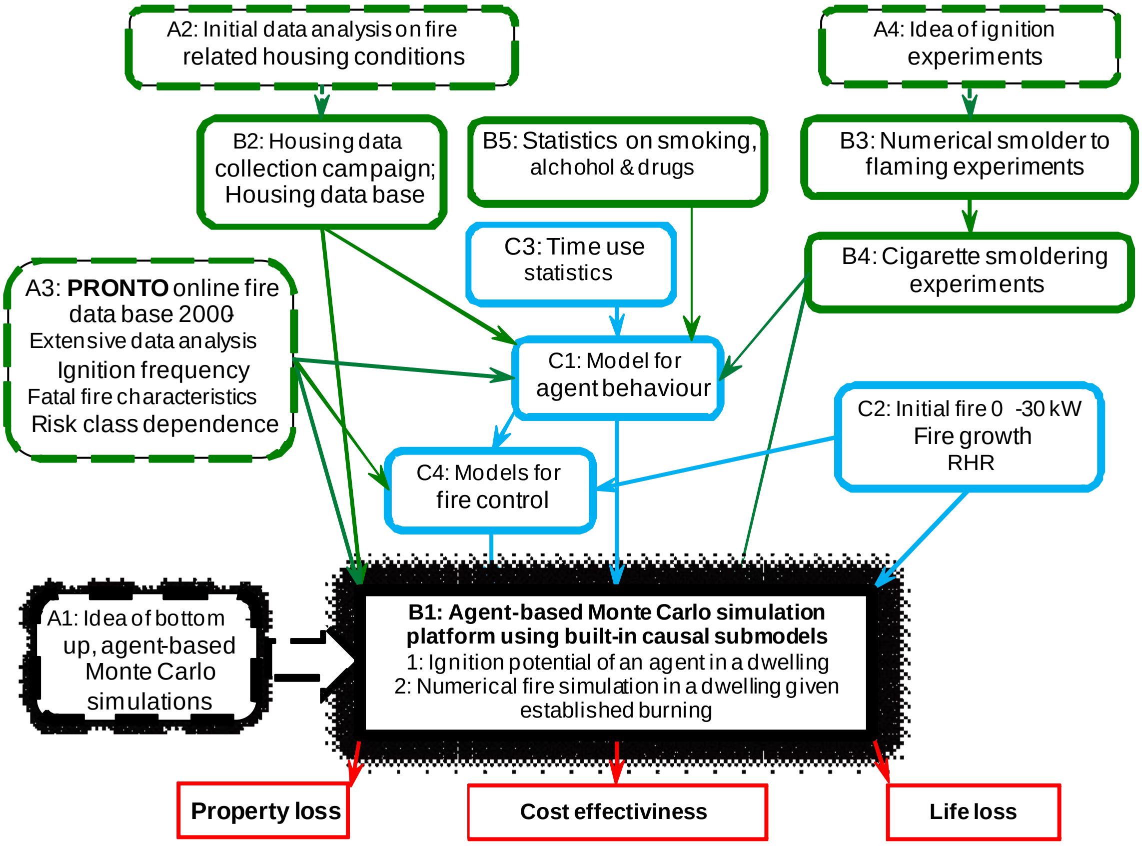

Figure 1. Subtask scheme for developing and testing the Monte Carlo simulation platform.

2.2. Subtasks

A2: Existing fire load information [5] were studied and housing data collected earlier by Emergency Services College students in Kuopio as home exercises were analyzed [6]. An updated plan for a wider collection campaign was made for subtask B2. A3: Extensive analysis of PRONTO data since 2000 was carried out to characterize fires and to find material, against which model predictions could be compared. Although life loss estimation was the major goal, property loss prediction was included from the beginning, because reliable statistical data was for them available more abundantly [7]. A4: Earlier studies on fatal fires [1] showed smoking is a significant ignition source in fatal fires, thus smoldering was a major theme. Plans for numerical (B3) and physical (B4) smolder experiments were made.

B1: Monte Carlo simulations of a home as the basic unit were carried out in two phases flaming ignition as the borderline. Burning was supposed local as long as fire is smaller than the established burning (flame height 30 cm), and no fire simulation was needed yet. As fire grows bigger, fire department is informed. Those fires are recorded in PRONTO data base.

(B1.1) Ignition potential of an agent was supposed to depend on its behavior and characteristics. For fast pre-flaming simulations we used statistical data provided by Statistics Finland on population, buildings, households, and time-use (C3). Data by National Institute for Health and Welfare on health behavior was reworked (in B5) to calculate smoking, drinking, use of relevant medication, and blood alcohol concentration. Fire ignition following a smoking initiation was modeled as a Poisson process [8]. Similarly, ignition of household appliances and other ignition sources like those connected to cooking were modeled. A household was simulated for a single calendar year in time steps of 10 minutes (using time use data from C3) unless an ignition occurred. Parameters were adjusted until the number of ignitions agreed with statistical data. Diurnal, weekly and yearly cycles of recorded ignitions (Fig. 2) served as additional tests for our sub-models. Once an ignition occurred, all data were stored to be used as the input for the second phase (B1.2) of simulation. PRONTO fire reports are made, if a fire department is alarmed. The number of open fire ignitions is an order of magnitude larger. Therefore, subunits C1 and C4 were added to model in detail local, almost reflective fire extinguishment as well as local fire control measures. In case these are successful, no fire alarm is made. The challenge for modeling is limited information available on those processes.

(B1.2) Given established burning room fire simulation determines the conditions in the dwelling. These - taking much longer computer time - were simulated using our earlier platform, and the effects from fires on humans were calculated in the established way. Our earlier method [9] was used for RHR prediction as a function of fire load and room opening dimensions. The most sensitive parameter is fire growth time, which was selected from experimental lognormal distribution The model was tested using room configurations and fire loads from A2. Subtask C2 was added to detail in this subject. Alarm after ignition as well as reactions and operations of household members, neighbors and fire department as well as fire protection equipment were modeled (C1 and C4) for the second round of Monte Carlo simulations, where fire development in the home was the driving force. Blood alcohol concentration, use of medication, and other impairing factors were used modeling agents for escape calculations. Simulations were carried out as long as life and property loss estimations made necessary. Fire was confined in the home of origin. This limitation has little effect on life loss but is significant on large property loss.

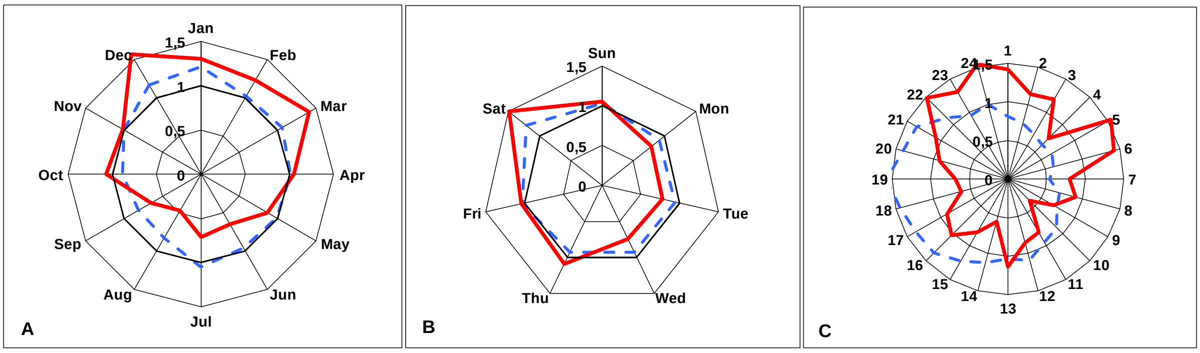

Figure 2. (a) Annual, (b) weekly and (c) diurnal variation of ignition frequency of residential fires during years 2002-07; full thick line: fatal fires, dashed line: residential fires, thin polygonal line: average over the cycle = 1.

3. RESULTS FROM SUBTASKS

3.1. Fire ignition frequency

In subtask B2 PRONTO data base combined with building stock data from Statistics Finland allowed quantification of fire ignition frequency. The basic idea of Barrois [10] modernized by Ramachandran [11] was reworked to the generalized Barrios' model [12 - 13]. It describes ignition frequency per floor area *f''(A)* as a function of building category and floor area *A*

$$f''(A) = c_1 A^r + c_2 A^s, \qquad (1)$$

The function fitted for the whole Finland is plotted in Fig. 3 for residential buildings with values of parameters shown in the inset. For fire risk analysis the whole country is divided by a grid into square cells of 250 m. Each cell is ranked for fire risk by inhabitants, building floor area and number of road accidents. The neighboring cells are combined to risk zones I – IV in descending order. Equation 1, which uses a building as a the basic unit, was modified for each grid cell. Ignition frequencies were summed up and adjusted to agree with statistical observations. Therefore, number of fires in our model is not calculated but is based on real observations. Even within a community, there is micro-area differentiation as shown in Fig. 4. Left panel shows fatal fires annually by million inhabitants by risk zones. Probability of a fatal fire is 3.4 times higher in zone IV than in zones I-III on the average. Similar behavior is shown in structural fires (middle panel) and emergent incidents (right panel). Since fires are mainly man-caused, in each community there is social differentiation and stratification manifesting so strikingly.

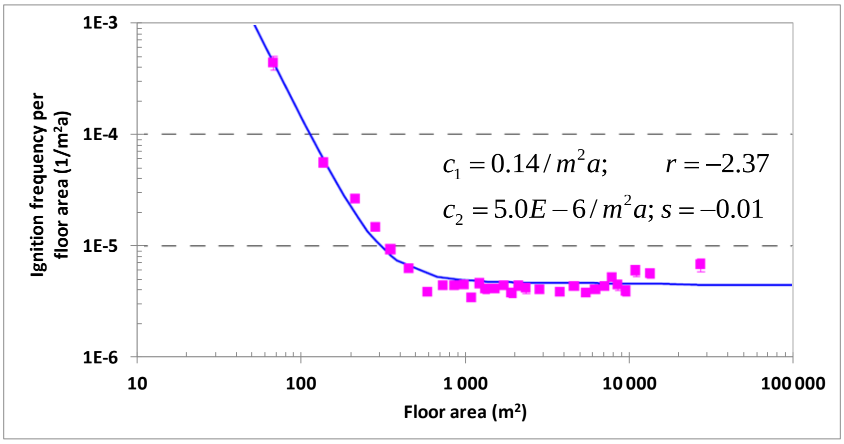

Figure 3. Annual ignition frequency per floor area [$1/m^2a$] of residential buildings in Finland, [14].

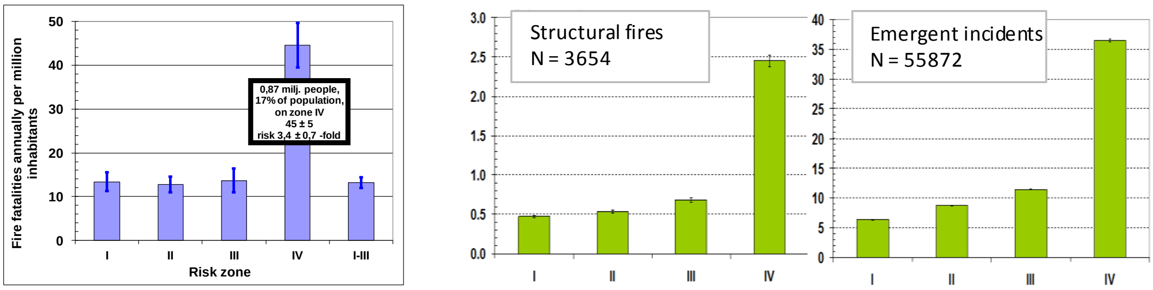

Figure 4. Frequency of fatal fires per million inhabitants as well as structural fires and emergent incidents per thousand inhabitants on risk zones I - IV in Finland.

3.2. Fire damage distributions

Material fire loss distribution, given in PRONTO also as damaged floor area *A*, is described well by Weibull distribution [15, 8] for premises below 100 m^2. In Fig. 5a survival function *S* of the distribution is plotted for all residential fires (N = 3347) and for fatal fires (N = 149).

$$S(A;\alpha,A_0) = 1 - F(A;\alpha,A_0) = \exp(-(A/A_0)^{\alpha}), \qquad (2)$$

The fitted curves (full lines) hide behind observed dots on linear plot (a), but deviate clearly for larger dwellings a shown on logarithmic plot (b). Hazard function *h*

$$h(A;\alpha,A_0) = (\alpha/A_0)(A/A_0)^{\alpha-1} \qquad (3)$$

for all residential fires is decreasing function of A (full line) but for fatal fires increases (dashed line). The former is known in reliability engineering as “infant mortality” and the latter as “wear out” curves. Interpretation of results ‘in the language of fire protection’: System response becomes more effective as damage size grows, whereas for fatal fires it weakens with progress of fire. In bigger buildings there are more variations (Fig. 5b), but it is not discussed here.

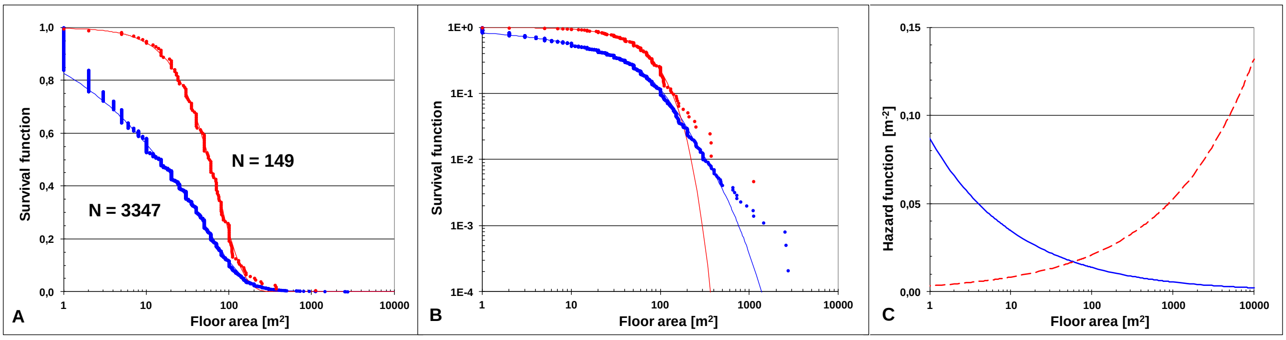

Figure 5. (a) The survival function of fire loss area is well described by a Weibull distribution below 100 m^2, (b) but for larger buildings more complicated behavior occurs. (c) Hazard function of all building fires (full line) and fatal fires (dashed line).

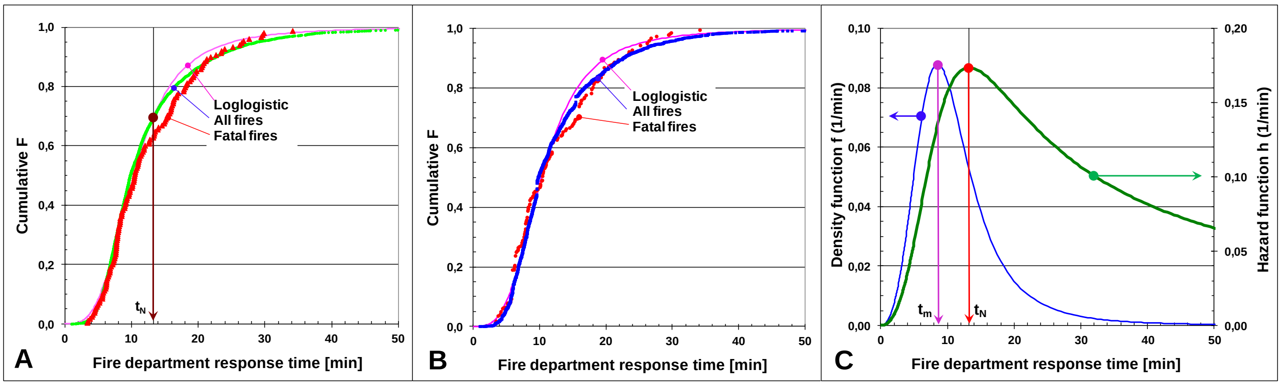

Figure 6. (a) Cumulative distribution F of response time of rescue service for residential fires. (b) Cumulative distribution F of fire loss area as a function of response time of rescue service. (c) Density function f (left scale) and hazard function h (right scale) from the log-logistic fit.

Cumulative distribution F of fire department response time for the same data as in Fig. 5 is plotted in Fig 6a for all and fatal fires. Differences between distributions are fairly small. Cumulative distribution F of fire loss area as a function of response time is plotted in Fig. 6b again for all and fatal fires. Distributions are almost identical. What is even more surprising, is that on all four data sets a good fit was made by the same log-logistic [16, 8] cumulative distribution

$$F(t;n,\tau) = (1+(\tau/t)^n)^{-1}, \qquad (4)$$

where fitting parameters $n \approx 3.3$ and $\tau \approx 10.3$ min. The fitted curves are shown in full line in Fig. 6a and 6b. In Fig. 6c are plotted using fitted parameters the density function f

$$f(t;n,\tau) = (n/\tau)(\tau/t)^{n+1}(1+(\tau/t)^n)^{-2} \qquad (5)$$

and the hazard function h

$$h(t;n,\tau) = (n/t)(1+(\tau/t)^n)^{-1} \qquad (6)$$

of the log-logistic distribution. The mode time of the density distribution t_m

$$t_m = \tau((n-1)/(n+1))^{1/n} \quad (7)$$

and the time t_N,

$$t_N = \tau(n-1)^{1/n} \quad (8)$$

the hazard function has a maximum, are important times when characterizing fire department response. Fitting of log-logistic curve to response time distribution was found experimentally earlier [17], but not understood. If two factors in a multiplicative system are stronger than others, the distribution might be log-logistic. Distance and vehicle speeds are these pronounced variables.

While $t_m \approx 8.5$ min is the time fire department arrives on the scene most often, $t_N \approx 13.2$ min is the time fire department is, on the average, controlling the fires. Interpreting data in Fig. 6 we do it using analogy with industrial controlling systems. We look data as a product of a system. If fire occurs, there are several correcting responses acting simultaneously and influencing both on response time and fire loss, but timing is only available in PRONTO from fire department actions. Hazard function *h* in Fig. 6c is increasing and of "wear out" type for times $t < t_N$ showing response of decrepit system. Corrective actions take time to launch them. For times $t > t_N$ hazard function becomes decreasing "infant mortality" type, where with increasing time failure probability becomes smaller. Substituting in Eq. (4), it is seen $F(t_N; n, \tau) = 1 - 1/n \approx 0.70$ indicating, 70% of the alarms, as well as events causing life and property loss is included.

Time t_N is the best way to characterize by using one figure only both the fire challenge and the mitigation response. While response time is influenced by the equipment and personnel of the fire department as well as the geography of the operating region, the distributions in Fig 6a and 6b are influenced by several factors of all the community involved: people, building stock, fire prevention measures as well as climatic and other environmental and social conditions.

Figs. 6a indicates, is sharp contrast to Fig. 5a, that there is no difference between fatal and all fires in fire department actions. In fact timing and statistics shows, majority of the victims are already dead when fire department arrives. This path of the events was confirmed by simulations in block B1.1. Same type of mechanism causes material losses as shown in Fig. 6b. Smoke spread within a home is so quick even if the fire seat is still small, that damage to property has already taken place before fire department actions.

3.3. From smoldering to flaming

From subtask A4 and B3 in Fig. 7 various one-dimensional smoldering modes are explained graphically. The smolder front is a thin zone progressing slowly towards unburned material. In buoyant systems oxygen (air) flow is caused by temperature differences. The front moves concurrent (A) or countercurrent (B). In forced systems air flow is caused by external forces independent of combustion. Also there, the front moves concurrent (C) or countercurrent (D).

Although interaction of a smoldering cigarette with a porous combustible material like clothing, upholstery or bed linen is never one-dimensional, approximate configurations can be given as shown below each mode of smoldering in Fig. 7. (A) Cigarette falls on airtight substrate and a combustible porous material fall later on it; a rare but possible event sequence for a careless smoker. (B) Combustible material on airtight substrate (floor), on which a cigarette falls; the most frequent potential ignition event for a careless smoker. (C) Cigarette in free air covered by a porous combustible, through which air is forced; possible but a rare event for a careless smoker; most favorable for smolder to flaming transition. (D) Porous combustible in free air; air forced through it; cigarette falls on the combustible; occurs automatically when a smoker falls in sleep; combustibles clothing or bed linen.

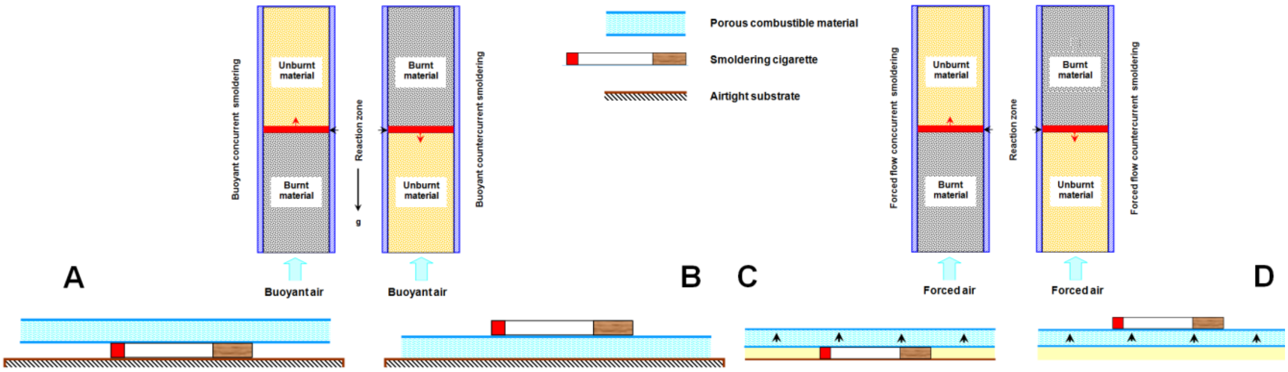

Figure 7. Four modes of one-dimensional smoldering together with relevant cigarette ignition scenarios.

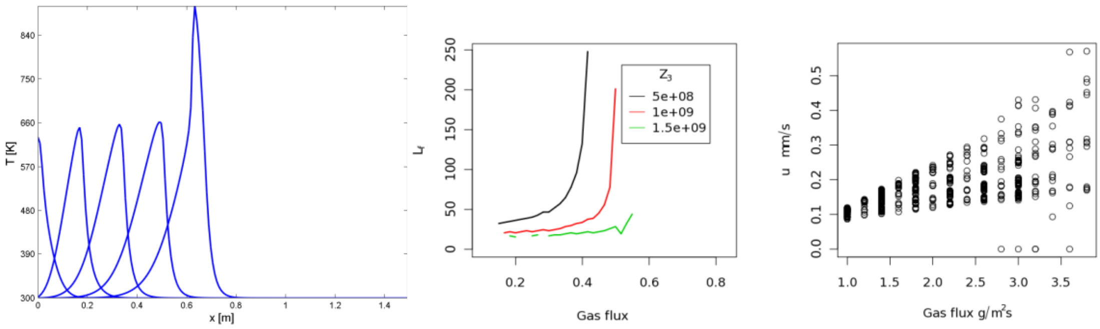

Figure 8. Left panel, evolution of the temperature of the smolder wave leading to a transition at $x = L_f = 0.64$ m. Middle panel, flaming length grows fast with gas flux before blowout. Right panel, velocity of smoldering front is approximately linear function of gas flux.

By simplified, ingenious analytic theory smoldering to flaming transition was shown to occur [18 - 20]. A numerical program Gpyro [21 - 23] was modified to simulate the smolder wave progress in polyurethane foam. A three reaction system was adopted: (i) flaming oxidation and (ii) pyrolysis of foam as well as (iii) glowing combustion of char to ash. Fig. 8 left panel shows temperature profiles at given locations as the smolder front passes through. Four first profiles from left have maximum temperature below 650 K, but the fifth profile at x = 0.64 m has a peak temperature of 900 K, which shows smolder is triggered to flaming at length L_f = 0.64 m in this system. Fig. 8 middle panel indicates flaming length depends on available gas flux, and grows quickly as the flux approaches blowout limit. At smaller fluxes (Fig. 8 right panel) velocity of smoldering front is approximately linear function of gas flux. The most important factor influencing flaming length L_f was the reaction rate (iii) of the char to ash. According to plentiful numerical experiments carried out randomly in the parameter space likely to be covered by real cigarette materials flaming lengths reached values easily found in practice. Furthermore, both con- and countercurrent smoldering geometries were found to be relevant.

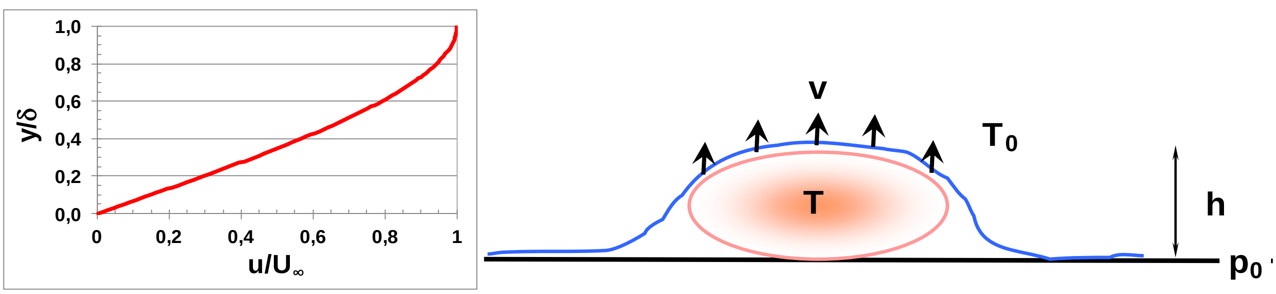

Figure 9. Left, velocity profile of boundary layer flow in a porous material. Right, forced flow field through the blanket or clothing of a laying person facilitates smoldering.

A boundary layer model [24] was used to calculate con-flow air velocity inside a porous material, where non-slip condition forces it to zero on an impermeable bottom substrate: $u = 0$ at $y = 0$ (Fig. 9 left panel). Free flow velocity $u = U_\infty$ along the top of the material. The model shows velocity u inside the material reaches a value $u = 0.5\,U_\infty$ at $y = 0.35\,\delta$, where δ is the thickness of the boundary layer. Therefore, porous materials on gastight substrate, like a carpet with pile on floor, or upholstery in furniture, are objects, where starting from the free surface there is sufficiently oxygen available for smoldering in most part of the material.

Prevailing flow velocities inside living premises, when all openings are closed, were estimated from ventilation norms: 2 – 5, 1 – 3, 0.4 – 0.9, and 0.04 – 0.3 mm/s in old, regular new, low-energy, and passive house buildings, respectively. In all cases the velocity is in the region supporting smoldering.

Figure 9 right panel shows schematically a cross section of a body of a person at temperature T lying under a blanket. The environment is at temperature $T_0 < T$; the difference in normal room conditions is 20 K. If the height of the body is $h = 0.3$ m, created pressure difference is of the order 0.2 Pa. Estimated forced flow velocity v through the blanket is in the range 0.7 – 5 mm/s using two rough measurements. This scenario is the same as shown in Fig. 7D, which occurs frequently as a smoking person falls in sleep. The flow field favors smoldering significantly. The other similar situation is created close to the mouth of a sleeping person. Breathing creates forced flow fields in nearby clothing, bed linen, mattresses and blankets, which facilitates smoldering if an ignited cigarette happens to fall on them.

3.4. Fire loads in living premises

A campaign (B2) carried out by students of Emergency Services College in Kuopio was arranged to collect fire relevant data from homes. Homes were not selected randomly, because they would not be available, but they reported either their own or homes from their inner circle. Sample size was increased to compensate for this biased selection. A considerable number of variables were measured [25], but here fire load data are shown graphically in Fig.10a for movable and 10b for fixed fire load for apartments, row houses and single family houses, respectively. In Fig. 10c total fire loads of all houses collected are plotted. A lognormal cumulative distribution function [8]

$$F(x) = \frac{1}{2}\left[1 + erf\left(\frac{\ln(x/\mu)}{\sigma\sqrt{2}}\right)\right], \qquad (9)$$

was fitted on the data as shown by a dashed line. Even a better fit was obtained using a sum of two lognormal functions

$$F(x;\mu,\sigma) = (1-c)F_1(x;\mu_1,\sigma_1) + cF_2(x;\mu_2,\sigma_2), \qquad (10)$$

The fitting parameters are given in Table 1 for all fire load distributions separately.

4. CONCLUSION

Development process and results from subtasks of the Monte Carlo calculation platform are described. Statistical analysis of PRONTO data enlightened the fire problem and allowed detailed estimation of fire frequency. For fatal fires the immediate ignition mitigation system – fire department excluded – is impaired. Fatalities occur so quickly, that fire department intervention is seldom successful. Models describing smolder to flaming were used to find relevant parameters for ignition in careless smoking. A campaign to collect fire load and other fire related information from homes was carried out and results were worked into a data base. Preliminary Monte Carlo simulations showed: (A) active age, (B) elderly, and (C) dependent persons formed three groups of victims, where the path to fatality was different. Therefore, also the means for improving fire safety must be designed differently for each of these groups. Social exclusion seems to be the major common factor for fire fatalities in group A, while the real reason is careless open fire use (smoking) for ignition and alcohol/drugs use to prevent escape. Memory disorders and physical difficulties are the major factors in group B. Women are a minority in group A but a majority in group B whereas children are very rare victims in group C, which is otherwise heterogeneous. Detailed large scale simulation results will be published later.

Table 1. Sample sizes, mean and standard deviations (SD) of collected fire loads in residential premises as well as fitting parameters of fire load distributions.

Housing type	**N**	**Mean** MJ/m^2	**SD** MJ/m^2	μ_1 MJ/m^2	σ_1	**c**	μ_2 MJ/m^2	σ_2
Total fire load of all premises	314	492	346	250	0.70	0.60	630	0.59
- Movable	314	348	364	10	0.95	0.06	255	0.86
- Fixed	314	146	73	60	0.30	0.75	340	0.55
Apartment houses	206	372	142	120	0.28	0.05	360	0.37
- Movable	206	309	145	75	0.30	0.05	290	0.45
- Fixed	206	63	27	52	0.38	0.97	260	0.55
Single family houses	50	520	180	470	0.36	0.80	580	0.25
- Movable	50	292	127	135	0.20	0.05	275	0.42
- Fixed	50	225	80	95	0.28	0.43	300	0.36
Row houses	46	433	171	380	0.40	0.90	600	0.26
- Movable	46	292	135	120	0.80	0.15	290	0.40
- Fixed	46	145	83	100	0.40	0.90	300	0.26

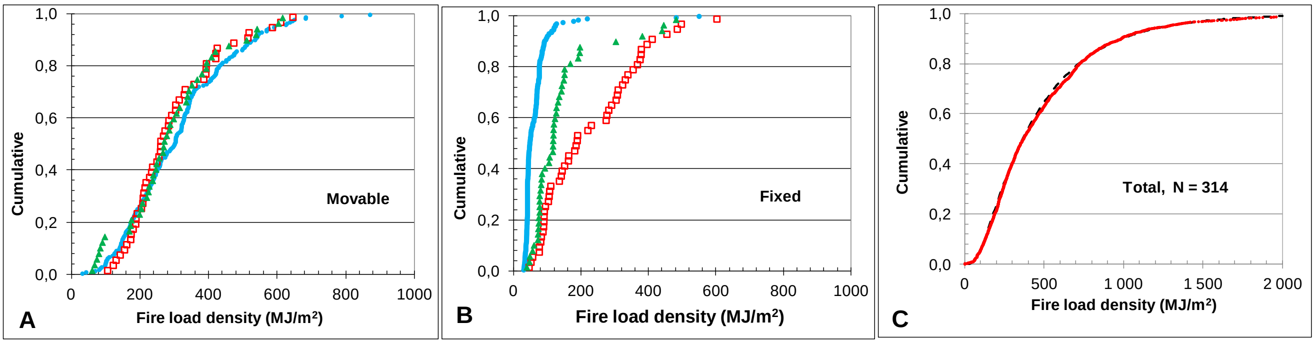

Figure 10. Cumulative fire load density (MJ/m^2) distribution from observations: (A) movable and (B) fixed (apartments: dots, row houses: triangles, single family houses: squares). (C) Observations of total fire load of all residential houses (dots) with a fit of two lognormal distributions (dashed line), which hardly shows below the dots.

Acknowledgements

The study was financed by Fire Protection Fund, Ministry of Interior, Ministry of the Environment, Ministry of Social Affairs and Health, and VTT. Emergency Services College facilities, faculty and students were invaluable in large scale campaigns. National Institute for Health and Welfare and Statistics Finland delivered essential sets of statistical data.

References

[1] Rahikainen, J. & Keski-Rahkonen, O., 2001. Fire deaths in Finland 1988 - 1997, in Proceedings of the 2nd International Symposium on HumanBehaviour in Fire 2001. Cambridge, Boston, 26 - 28 March 2001. Interscience Communications. London (2001), pp. 489 - 496.

[2] Hostikka, S., Keski-Rahkonen, O., Marttila, J. & Virolainen, R., 2000. Determination of cumulative ignition time distribution for PSA of the next target in case of a potential cable tunnel fire of a NPP. In PSAM 5. Proceedings of the 5th International Conference on Probabilistic Safety Assessment and Management. Osaka, JP, 27 Nov. - 1 Dec. 2000. Kondo, S. & Furuta, K. (eds.). Universal Academy Press. Tokyo (2000), pp. 2099 - 2104.

[3] Hostikka, S., Keski-Rahkonen, O. & Korhonen, T., Probabilistic Fire Simulator. Theory and User's Manual for Version 1.2, VTT Publications 503, 2003. VTT Rakennus- ja yhdyskuntatekniikka, Espoo. 72 p. + app. 1 p.
[4] McGrattan, K., Hostikka, S., Floyd, J., Baum, H., Rehm, R., Mell, W. & McDermott, R., 2010. Fire Dynamics Simulator (Version 5), Technical Reference Guide, Volume 1: Mathematical Model, NIST Special Publication 1018-5, SVN Repository Revision : 6909, FDS Version 5.5, 108 p.
[5] Korpela, K. & Keski-Rahkonen, O., 2000. Fire loads in office buildings. In: Proceedings of the 3rd International Conference on Performance-Based Codes and Fire Safety Design Methods, Lund, Sweden , 15-17 June 2000. Lund: Lund University, pp. 278-286.
[6] Keski-Rahkonen, O., Karhula, T. & Hostikka, S., 2009. Palokuormien jakaumat palokuoleman ehkäisykeinojen arviointiohjelmassa [Fire load distributions analyzed for the fire death research program], Pelastustieto 60, palontorjunta-tekniikka-erikoisnumero - Palotutkimuksen päivät 2009, 108–114, (in Finnish).
[7] Tillander, K. & Keski-Rahkonen, O., 2004. Property loss in structural fires in Finland, INTERFLAM 2004: proceedings of the 10th International Fires Science & Engineering Conference, Edinburgh, Scotland, 5-7 July 2004. Interscience Communications, London, 2004. Vol 1, pp. 313 – 324.
[8] McCormick, N.J., 1981. Reliability and Risk Analysis – Methods and Nuclear Power Applications, Orlando, FA, Academic, 446 p.
[9] Keski-Rahkonen, O., 1993. Design fire construction for individual assessment, 3rd CIB/W14 Workshop Modelling, 25 - 26 Jan. 1993. Proceedings. Twilt, L. (Ed.). TNO Building and Construction Research. Rijswijk (1995), pp. 43 – 48.
[10] Barrois, T.J., 1834. Essai sur l'application du calcul des probabilités aux assurances contre les incendies, Mémoires de la société royale des sciences, de l'agriculture et des arts de Lille, 11, 85–282.
[11] Ramachandran, G., 1998. The Economics of Fire Protection, London, E & F Spon, 230 p.
[12] Rahikainen, J. & Keski-Rahkonen, O., 1998. Determination of ignition frequency of fires in different premises in Finland. Fire Engineers Journal, Nov, 33 - 37.
[13] Rahikainen, J. & Keski-Rahkonen, O.. 2004. Statistical determination of ignition frequency of structural fires in different premises in Finland, Fire Technology, 40, 335-353.
[14] Tillander, K., Oksanen, T. & Kokki, E., 2009. Paloriskin arvioinnin tilastopohjaiset tiedot [Statistical data for fire risk assessment], VTT Tiedotteita – Research Notes 2479, VTT, Espoo, 106 p. + App. 5 p., [in Finnish].
[15] Weibull, W. 1939. A statistical theory of the strength of materials, Ingeniörsvetenskaps-akademiens handlingar Nr 151, Stockholm, 45 p.
[16] Verhulst, P.-F., 1838. Notice sur la loi que la population suit dans son accroissement, Correspondance mathématique et physique, 10, 113-121.
[17] Tillander, K., Korhonen, T. & Keski-Rahkonen, O., 2005. Pelastustoimen määräiset seurantamittarit [Quantitative indicators for rescue service], VTT Working Papers 19, VTT-WORK-19, Espoo, 122 p. + App. 5 p., [in Finnish]
[18] Aldushin, A.P., Bayliss A. & Matkowsky, B.J., 2009. Is there a transition to flaming in re-verse smolder waves?, Combustion and Flame, 156, 2231 – 2251.
[19] Aldushin, A.P., Bayliss A. & Matkowsky, B.J., 2007. On the mechanism of triggering the transition from smoldering to flaming, Proceedings of the Combustion Institute, 31, 2661–2668.
[20] Aldushin, A.P., Bayliss A. & Matkowsky, B.J., 2006. On the Transition from smoldering to flaming, Combustion and Flame 145, 579-606.
[21] Rein, G.J., 2005. Computational Model of Forward and Opposed Smoldering Combustion with Improved Chemical Kinetics, PhD thesis, The University of California at Berkeley, 171 p.
[22] Rein, G., Lautenberger, C., Fernandez-Pello, A.C., Torero, J.L., Urban, D.L., 2006. Application of genetic algorithms and thermogravimetry to determine the kinetics of polyurethane foam in smoldering combustion, Combustion and Flame, 146, 95–108.
[23] Rein, G., Bar-Ilan, A., Fernandez-Pello, A. C., Ellzey, J. L., Torero, J. L. & Urban, D. L., 2005. Modeling of One-Dimensional Smoldering of Polyurethane in Microgravity Conditions, Combustion Institute, Symposium (International) on Combustion, 30th. Proceedings. Volume 30. Part 2. July 25-30, 2004, Chicago, IL, Combustion Institute, Pittsburgh, PA, Chen, J. H., Colket, M. D., Barlow, R. S. & Yetter, R. A., (Editors), p. 2327-2334.
[24] Nideld, D.A. & Bejan, A., 2006. Convection in Porous Media, Springer, Third Edition, 640 p.
[25] Karhula, T., Ryynänen, J. & Keski-Rahkonen, O., 2011. Miten tulipalo näkee Suomen asuntokannan ? [How fires see the Finnish building stock ?], Pelastustieto, 62, Palontorjuntatekniikka-erikoisnumero, 12-16, [in Finnish].