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Evaluation Models of Effectiveness of Hose Rescue Equipment used in Evacuation of People from High-Rise Buildings

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Abstract: The researchers of the study offer use of hose rescue equipment for evacuation of people from high-rise buildings in case of fire or emergencies. Two model classes were developed (space balance model and mass service models for evacuation description with hose rescue equipment used). These models allow for evaluation of effectiveness of hose rescue equipment use during evacuation.

Key words: Evacuation, high-rise buildings, hose rescue equipment, effectiveness of use, model, evacuation

INTRODUCTION

The current trend of increasing rates of human death and injuries caused by fires in high-rise buildings requires introduction of new safety tools and methods aimed at preserving life and health of people (Gwynne *et al*., 1999; Hamacher and Tjandra, 2001). Use of various rescue evacuation equipment and individual respiratory and eye protection against fire hazards is one of the promising ways to solve this problem (Dimakis *et al*., 2010; Matveev and Ivanov, 2011).

Relevance of use of rescue equipment for evacuation from height in case of fires at mass gathering facilities is determined by the fact that it is these facilities that usually create mass gathering of people when they follow the main evacuation routes (Wang *et al*., 2008). Gathering of people will cause significant increase in evacuation time and consequently will lead to exposure of people to fire hazards (Kholshchevnikov, 2015; Thompson and Marchant, 1995). Fires inflict the biggest social and pecuniary damage in the mass gathering buildings (Barham, 1996; Kuligowski *et al*., 2005).

MATERIALS AND METHODS

Solution methods: Hose Rescue Equipment (HRE) is one of the most effective means for human rescue from high-rise buildings in case of fire, especially in the mass gathering setting. Thus, examination of effectiveness of rescue equipment use and substantiation of the methods for its improvement is considered pending.

Tight rescue hoses have become wide-spread in Russia. They consist of a durable and non-stretching inner layer and an elastic outer layer. HRE operating principle (Fig. 1) is based on the significant friction force formed when the elastic fabric tightly enwraps the body moving inside the hose

By spreading one's elbows to the sides or pulling them together, one can easily control the speed of descent. The person who is not able to move independently can be descended on the shoulders of a physically healthy person a child can be pressed tight to the chest of a grown-up. Rescuers can control the speed and trajectory of descend by wringing or pulling the hose down.

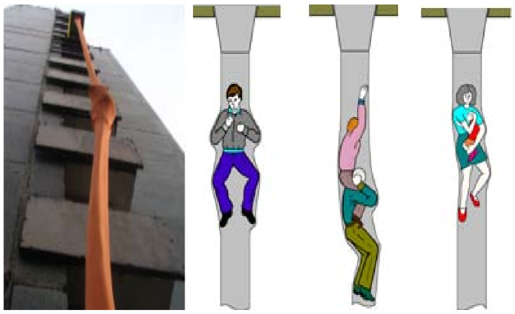

Fig. 1: Rescue hose

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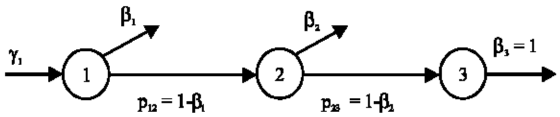

Fig. 2: Network model of evacuation system with HRE used; network junction points; 1: platform for entering HRE; 2: «platform» for escaping from the hose, 3: «safe place». Vectors g, m, m, b, R characterize intensity of external input flows and entry handling, network composition, external flow, permissible quantity of entries at the junction points; P: transfer matrices

HRE can be located outside or inside the building with simultaneous entrances from several levels. A hose is stored folded inside a container and is unfolded when necessary. Different structures that make installation of hoses on building facades (in window apertures on balconies and loggias on roofing) possible have been developed.

Evacuation of people using HRE can be tenuously divided into two stages. The first stage starts with receiving the alert and includes all actions of people (getting dressed, collecting things and documents, moving along the corridor, etc.,) all the way to escaping to the platform before the hose. The second stage includes entering the hose, moving down it, landing and escaping to a safe zone. The evacuation results depend on such factors as time taken to reach the platform, time taken to enter the hose and escape from it after landing, speed of descend, hose capacity. To assess effectiveness and develop recommendations on the most rational use of rescue equipment, we can use analytical (Matveev and Efremov, 2013; Matveev *et al.*, 2011) and simulation modeling methods. Figure 2 shows the network model of evacuation system with HRE used.

RESULTS AND DISCUSSION

Space balance model for evacuation description with HRE used: The system specification without detailed description of discrete processes can be evaluated using space balance models.

Position workload evaluation: Let's calculate the factors of use of rescue hose entry positions and of hose escaping positions at the evacuee flow intensity $\gamma_1 = 5\ \text{min}^{-1}$.

Let's assume that the proportion of people who could not reach the platform before the hose, $\beta_1 = 0.1$, proportion of people who couldn't escape from the hose, $\beta_2 = 0.05$, hose entering time $T_1 = 10$ sec, hose escaping time $T_2 = 4$ sec.

The model (Fig. 2) suggests that $p_{12} = 1\text{-}\beta_1 = 0.9$, $p_{23} = 1\text{-}\beta_2 = 0.95$. Based on the network balance equation, define the input flow intensity:

$$\begin{cases}\lambda_1 = \gamma_1\\ \lambda_2 = p_{12}\lambda_1\\ \lambda_3 = p_{23}\lambda_2\end{cases} \Rightarrow \begin{cases}\lambda_1 = 5\\ \lambda_2 = 4.5\\ \lambda_3 = 4.275\end{cases}$$

Service intensities: $\mu_1 = 1/T_1 = 6\ \text{min}^{-1}$, $\mu_2 = 1/T_2 = 15\ \text{min}^{-1}$, $\mu_3 = \infty$ (let's suggest that there are neither time nor space limitations when escaping to a safe place). Position occupation ratios $\rho_1 = \lambda_1/\mu_1 = 5/6$, $\rho_2 = 3/10$, $\rho_3 = 0$. The steady-state conditions $\rho \le 1$ are reached. The hose entry position is the most occupied one.

Definition of queue condition: Let's calculate the intensity of external flow into junction point 1 that would not create a queue in the system.

As junction point 1 is the most occupied one and no-queue condition is $\rho_1 \le 1$, we have $\lambda_1 \le \mu_1$ therefore, $\gamma_1 = \lambda_1 \le \mu_1 = 6\ \text{min}^{-1}$. Hence, the maximum evacuee flow to the pre-hose position that would not create a queue equals to 12 persons/min. Theory, Ventzel and Ovcharov suggests the equation that defines a maximum possible actual capacity:

$$\overline{Q} = \gamma_0^* \sum_{i \in I} \varepsilon_i \beta_i,\ \gamma_0^* = \max_{\gamma 0}\{\gamma_0:\ \gamma_0 \le m_i \mu_i/\varepsilon_i,\ i = 1, ..., n\}$$

Where:

γ_0^* = Maximum possible entry flow

i = Multitude of "escape" junction points except for the junctions points definite elements (in our case-injured people) are removed from

ε_i = Meets the combined equations $\varepsilon_i = \overline{\gamma}_i + \sum_{j=1}^{n} p_{ji}\varepsilon_j$, i = 1, ..., n and the meaning

$\overline{\gamma}_i$ = The share of the total external flow that starts to be services in ith junction point

Estimation of the maximum possible capacity of the human evacuation system that uses a rescue hose: As the external entry flow is only in junction point $1, \overline{\gamma}_1 = 1, \overline{\gamma}_2 = \overline{\gamma}_3 = 0$. Combined equations for ε_i definition will be written as:

$$\begin{cases}\varepsilon_1 = 1,\\ \varepsilon_2 = p_{12}\varepsilon_1\\ \varepsilon_3 = p_{23}\varepsilon_2\end{cases} \Rightarrow \begin{cases}\varepsilon_1 = 1\\ \varepsilon_2 = 0.9\\ \varepsilon_3 = 0.855\end{cases}$$

Maximum actual capacity value:

$$\gamma_0^* = 6\ \text{per/min},\ \overline{Q} = \gamma_0^* \varepsilon_3 \beta_3 = 5.13\ \text{per/min}$$

(per/min-persons/min). To increase the system capacity, "debottlenecking" method can be used. According to this method, the "bottleneck" junction point is equipped with another unit and the "bottleneck" is estimated at the new conditions. This process is kept on until the required capacity is reached.

Preset capacity synthesis: Let's form a system with preset capacity of 10 persons/minute. As junction point 1 is the "bottleneck" at preset junction point service intensities and unit quantity m = $(1, 1, 1)^T$, let's add one unit to this junction point and thus, we have:

$$\gamma_0^* = m_2\mu_2/\varepsilon_2 = 6.67 \text{ per/min}, \bar{Q}_\Phi = \gamma_0^*\varepsilon_3\beta_3 = 5.7 \text{ per/min}$$

The required capacity is not reached. Now, junction point 2 has become the "bottleneck". By adding the second unit (second hose) to it, we have:

$$\gamma_0^* = m_1\mu_1/\varepsilon_2 = 12 \text{ per/min}, \bar{Q}_\Phi = \gamma_0^*\varepsilon_3\beta_3 = 10.26 \text{ per/min}$$

Thus, to provide the actual system capacity of 10 persons/min at the adopted values of entry flow intensity, HRE entry and escape time, we should use two rescue hoses or one hose with a higher capacity or we should make the existing hose entry and exit more comfortable.

Conclusion: Balance models are characterized with simplicity but the conclusions based only on space estimations can be incorrect as they do not take into account the process discreteness, irregularity in element operation. Chance mathematic models based on the Mass Service Theory (MST) are used to estimate process instability.

Mass service model for describing evacuation with HRE used

Basic model parameters: In the reviewed system of evacuation of people from high-rise buildings using HRE, the parameters of the Mass Service System (MSS) presented in Kendall form A/B/m/R/N/d (Kijima, 1997; Ethier and Kurtz, 1986; Kendall, 1951) are interpreted as:

- Channel or MSS unit-tight hose (or hose entry and hose escape platforms)
- Claim or demand-evacuated person
- R-amount of people who have arrived at the evacuation position and can wait for the moment of hose availability
- N-amount of people to be evacuated
- d-FIFO discipline is usually characteristic of ES (the first person to arrive is serviced)
- A(t)-exponent function of timing between ingress of people to evacuation equipment
- The type of service time distribution function B(t) is associated with the "capacity" of the rescue hose and different affecting factors, in particular, hose reliability, physical and psychological evacuee condition, their age, gender, etc

Evacuation model with one rescue hose used: At first, let's review the models that describe the main evacuation option with one rescue hose. For the study, it is necessary to know the intensity of arrival of people at the pre-HRE platform. In case of highly indefinite characteristics, the best results are obtained through the use of exponential distribution which is characterized only by one parameter-average value. Hose entry time is also incidental but here everything is determined, basically, only by human skills.

Let's consider the interval between arrival of people at the pre-hose platform to be an incidental value that has the exponential distribution law with average T_1, HRE entry time to be an exponentially distributed incidental value with average T_2.

Let's proceed with the following model. A "flow of people" with exponential intensity distribution $\lambda = 1/T_1$ arrives at the rescue hose. The hose-entry process also has exponential distribution with intensity (average rate) $\mu = 1/T_2$. Such model corresponds exactly with the analytical MSS model of M/M/1 type. In particular with T_1 = 10 sec, T_2 = 5, we have (Khinchin *et al.*, 2013):

- Pre-hose position loading factor $\rho = \lambda/\mu = 0.5$
- Average total amount of people currently staying on the platform and in the hose, $\bar{u} = \rho/(1-\rho) = 1$
- Average amount of people standing in the hose-entry queue, $\bar{v} = \rho^2/(1-\rho) = 0.5$
- Average time of staying in the system $\bar{\theta} = \bar{u}/\lambda = 10$ sec
- Average hose-entry waiting time $\bar{\vartheta} = \bar{v}/\lambda = 5$ sec

The analysis allows for the following conclusions: The entry factor increases fast when T_1 and T_2 close-in. Besides, hose-entry queues and the entry waiting time increase. The average hose-entry time T_2 shall be less than the average interval T_1 between "arrivals" of people at an entry position. Otherwise, people will gather before the hose that can result in additional problems due to the limited platform size. At the hose-entry time T_2 = 5 sec, the maximum hose carrying capacity equals to 12 people per minute. This may be not insufficient for evacuating all people. That's why additional measures to increase the carrying capacity shall be taken, for example, creation of another "rescue channel" with the second hose or improvement of the "method of loading" of people into the hose.

One of possible rescue procedures in case of fire or an emergency situation suggests control of evacuee flow from outside the building (Elms *et al*., 1984; Steere, 1964). In particular, "cutting" of the human flow from the hose can be considered to obtain strictly uniform entry in determined time T_2. In this case, MSS model of M/D/1 type and the following characteristics can be used (Viswanadham and Narahari, 1992):

- Average amount of demands in the system

$$\bar{u} = \rho \cdot (2\text{-}\rho)/2(1\text{-}\rho);\ \text{at}\ \rho = 0.5\ \bar{u} = 0.75$$

- Average amount of claims for service in the queue

$$\bar{v} = \rho^2/2(1\text{-}\rho);\ \text{at}\ \rho = 0.5\ \bar{v} = 0.5$$

- Average time of staying in the system

$$\bar{\theta} = (2\text{-}\rho)\cdot T_2/2(1\text{-}\rho);\ \text{at}\ \rho = 0.5 \text{И} T_2 = 5\ \text{sec}\ \bar{\theta} = 0.5\ \text{sec}$$

- Average time of waiting for service

$$\bar{\vartheta} = \rho\cdot T_2/2(1\text{-}\rho);\ \text{at}\ \rho = 0.5\ \text{and}\ T_2 = 5\ \text{sec}\ \bar{\vartheta} = 5\ \text{sec}$$

Comparison with the M/M/1 model shows that in case of a determined "flow through the hose", the average number of evacuees and the average time of evacuation decreases compared to the exponential flow by (2–ρ)/2 times and the average queue and the average time of staying in the queue to the rescue hose by 2 times. Thus, in case of a high hose loading ($\rho\to 1$), the human flow control will be rather effective.

Let's review the influence of the non-uniqueness (variance) of hose-entry time based on the normal law of distribution of this incidental value with the average T_2 and dispersion σ^2. We have the standard case of MSS model of M/G/1 type with the variation ratio $c_x = \sigma/T_2$. The basic characteristics are calculated based on the equations (Khinchin *et al*., 2013):

- Average number of claims in the system

$$\bar{u} = \rho+\rho^2\times(1+c_x^2)/2(1\text{-}\rho);\ \text{at}\ \rho = 0.5\ \text{and}\ c_x = 1\ \bar{u} = 0.76$$

- Average amount of claims for service in the queue

$$\bar{v} = \rho^2\cdot(1+c_x^2)/2(1\text{-}\rho);\ \text{at}\ \rho = 0.5\ \text{and}\ c_x = 1\ \bar{v} = 0.26$$

- Average time of staying in the system

$$\bar{\theta} = T_2 + \rho\cdot T_2\cdot(1+c_x^2)/2(1\text{-}\rho);\ \text{at}\ \rho=0.5\ \text{and}\ T_2 = 5\text{c}\ \bar{\theta} = 7.6\ \text{sec}$$

- Average time of waiting for service

$$\bar{\vartheta} = \rho\cdot T_2\cdot(1+c_x^2)/2(1-\rho);\ \text{atr} = 0.5\ \text{and}\ T_2 = 5\text{c} = 2.6\ \text{sec}$$

Increase of the variation ratio leads to quadratic (increase of dispersion to linear) increase in queue characteristics and evacuation time. For example, when the variation ration increases from 0-2 T_2, the average amount of people in the entry queue changes from 0.25-1.25 and the time of staying in the queue from 7.5-17.5 sec.

Evacuation model with two rescue hoses used: Effectiveness of use of an additional rescue hose can be studied based on the MSS model of M/M/m type with the amount of units m = 2. If T_1 = 10 sec, T_2 = 5 sec, we obtain the following characteristics:

- Entry position occupation ratio $\rho = \lambda/m$; $\mu = 0.25$
- Probability of absence of evacuees on the pre-hose platforms and of people entering the hoses

$$p_0 = \frac{1}{\sum_{k=0}^{m-1}\frac{(m\rho)^k}{k!}+\frac{(m\rho)^m}{m!(1\text{-}\rho)^2}} = \frac{1}{1+2\rho+\frac{(2\rho)^2}{2!(1\text{-}\rho)^2}} = 0.581$$

- Total amount of people currently staying on the platforms and entering the hoses

$$\bar{u} = p_0\left[\sum_{k=1}^{m-1}\frac{(m\rho)^k}{(k\text{-}1)!}+\frac{(m\rho)^m(\rho+m\text{-}m\rho)}{m!(1\text{-}\rho)^2}\right] = p_0\left(2\rho+\frac{(2\rho)^2(2\text{-}\rho)}{2!(1\text{-}\rho)^2}\right) = 0.484$$

- Average amount of people staying in the hose-entry queue

$$\bar{v} = p_0\cdot\left[\frac{\rho(m\rho)^m}{m!(1\text{-}\rho)^2}\right] = p_0\cdot\frac{\rho(2\rho)^2}{2!(1\text{-}\rho)^2} = 0.032$$

- Average entry time (with waiting) $\bar{\theta} = \bar{u}/\lambda$ = 4.84 sec
- Average time of waiting for hose entry $\bar{\vartheta} = \bar{v}/\lambda$ = 0.32 sec

The conclusions from the obtained results are obvious-availability of the second hose significantly reduces the queues and time of staying in them. This measure is especially effective in case of high entry ratios.

Limited queue evacuation model: Let's consider another important limitation. The platform of HRE may not house everybody interested for example, if it is located on a balcony of a residential building. Mass gathering can cause panic that can also result in negative consequences.

The above situation corresponds to the MSS model of M/M/1/R type (R-storage capacity). The theory suggests that probability of customer loss (or blocking probability) in such model is defined by the equation:

$$p_{бл} = p_R = \rho^R(1\text{-}\rho)/(1\text{-}\rho^{R+1})$$

Customer loss means death of people. That is why $p_{бл}$ shall be close to zero. The required storage capacity that provides for blocking probability not exceeding the preset value $\bar{p}$ equals to $R = \ln(\bar{p}/(1\text{-}\rho+\bar{p}\rho)/\ln\rho$. With $\bar{p} = 0.001$ and $\rho = 0.5$, R =10.

Increase in storage capacity gives some positive effect and the higher the position occupation ratio is the higher the effect is. This effect suggests that claims (people) will not disappear but will wait for their turn in the storage (on the platform).

CONCLUSION

The process of human descend in a rescue hose has also a number of peculiarities that shall be taken into account when studying the ES response system. The main of these peculiarities include:

- Possible movement of people at different speeds during descend
- Significant variance of the speed values
- Limited hose capacity

The first two aspects suggest that while moving people can keep up with each other proceeding in groups and this can result in injuries and make hose-escape more difficult after landing. Due to speed differences during descend, several people may land "on each other's heads". Clearly, it is much more difficult to escape from the hose in this case. Limited HRE capacity limits the maximum amount of people who can simultaneously stay within it.

But for these reasons, the process of evacuee movement in the rescue hose could be considered as a mere time delay (during descend) that enhances the time of staying in the system but does not affect queues and system capacity. Understandably such approach is not justifiable that is why the following "way out" is proposed.

Let's suggest that people, after landing, do not just leave the rescue hose but reach some contingent position called "hose-escape platform". To use this position and leave the hose to a safe place, definite time is needed. The value of this time is an incident measure as it depends on position (orientation) people land in their movement coordination and physical features on availability of the platform on people arriving alone or in groups, etc.

Using MST terms, the time of servicing people on the unit ("hose-escape platform") is incident. Clearly, the input flow defined by the rate the victims reach the hose and the hose-entry time is irregular, too. As before, nothing specific can be said about the character of laws describing these incident values. That's why it is most rational to consider the flows to be Poisson's. Within that narrative, the study can be implemented on the models described above. It is not reasonable to calculate them again; all the dependencies and conclusions are given and can be used.

Finally, the main estimations and conclusions in this article were obtained based on MST models and methods. These methods "work" well with the established operation regimes of the studied system that far from always complies with the development of the process of human evacuation from high-rise buildings. Number of tasks suggests analysis of transitory processes and requires stand-alone consideration in particular through the theory of probability and simulation modeling (Gupta *et al.*, 2001; Gwynne *et al.*, 2001, 1999; Kisko and Francis, 1985).

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REFERENCES

Barham, R., 1996. Fire Engineering and Emergency Planning. E & FN SPON, London, UL., ISBN:9780419201809, Pages: 586.

Dimakis, N., A. Filippoupolitis and E. Gelenbe, 2010. Distributed building evacuation simulator for smart emergency management. Comput. J., 53: 1384-1400.

Elms, D.G., A.H. Buchanan and J.W. Dusing, 1984. Modeling fire spread in buildings. Fire Technol., 20: 11-19.

Ethier, S.N. and T.G. Kurtz, 1986. Markov Processes: Characterization and Convergence. 2nd Edn., John Wiley and Sons, Hoboken, New Jersey, USA., Pages: 534.

Gupta, A.K., R. Kumar, P.K. Yadav and M. Naveen, 2001. Fire safety through mathematical modelling. Curr. Sci., 80: 18-26.

Gwynne, S., E.R. Galea, M. Owen, P.J. Lawrence and L. Filippidis, 1999. A review of the methodologies used in the computer simulation of evacuation from the built environment. Build. Environ., 34: 741-749.

Gwynne, S., E.R. Galea, P.J. Lawrence and L. Filippidis, 2001. Modelling occupant interaction with fire conditions using the buildingEXODUS evacuation model. Fire Saf. J., 36: 327-357.

Hamacher, H.W. and S.A. Tjandra, 2001. Mathematical Modelling of Evacuation Problems: A State of the Art. In: Pedestrian and Evacuation Dynamics, Schreckenberg, M. and S.D. Sharma (Eds.). Springer, Berlin, Germany, pp: 227-266.

Kendall, D.G., 1951. Some problems in the theory of queues. J. Royal Stati. Soc., 13: 151-185.

Khinchin, A.Y., D.M. Andrews and M.H. Quenouille, 2013. Mathematical Methods in the Theory of Queuing. Courier Corporation, North Chelmsford, Massachusetts, Pages: 126.

Kholshchevnikov, V.V., 2015. Experimental researches of human flow in staircases of high-rise buildings. Intl. J. Appl. Eng. Res., 10: 42549-42552.

Kijima, M., 1997. Markov Processes for Stochastic Modeling. Chapman&Hall, London, UK., ISBN:978-0-412-60660-7, Pages: 343.

Kisko, T.M. and R.L. Francis, 1985. EVACNET+: A computer program to determine optimal building evacuation plans. Fire Saf. J., 9: 211-220.

Kuligowski, E.D., R.D. Peacock and B.L. Hoskins, 2005. A review of building evacuation models. Master Thesis, US Deptartment of Commerce, National Institute of Standards and Technology, Gaithersburg, Maryland, USA.

Matveev A.V. and MV. Ivanov, 2011. Criterion of efficiency of manage by individual fire risk in a building with application of equipment of emergency evacuation, St. Petersburg State Polytechnical University. J. Comput. Sci. Telecommunications Control Syst., 6: 165-170.

Matveev, A.V. and S.V. Efremov, 2013. The model of the process of emergency evacuation from building in the case of fire at a nonstationary flow of people. Sci. Pract. Educ. Methodical J. Life Saf., 2: 46-50.

Matveev, A.V., M.V. Ivanov, V.Y. Piskov and D.Y. Minkin, 2011. The model of the system of management of emergency evacuation on the objects with the massive presence of people. Bull. Petersburg Univ. State Fire Serv., 4: 10-16.

Steere, N.V., 1964. Fire, emergency and rescue procedures. J. Chem. Educ., 41: A369-A375.

Thompson, P.A. and E.W. Marchant, 1995. A computer model for the evacuation of large building populations. Fire Saf. J., 24: 131-148.

Viswanadham, N. and Y. Narahari, 1992. Performance Modeling of Automated Manufacturing Systems. Prentice Hall, Upper Saddle River, New Jersey, USA., Pages: 585.

Wang, P., P.B. Luh, S.C. Chang and J. Sun, 2008. Modeling and optimization of crowd guidance for building emergency evacuation. Proceedings of the IEEE International Conference on Automation Science and Engineering CASE, August 23-26, 2008, IEEE, Arlington, Virginia, USA., ISBN: 978-1-4244-2022-3, pp: 328-334.