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An evolutionary approach for fire risk assessment in Brazilian slums

AM Claret
Fire Risk Analysis Laboratory, Federal University of Ouro Preto, Ouro Preto, MG, Brazil

EL Baranoski
State of Parana Fire Brigade Officer, Av. Nunes Machado, 100 – Curitiba, PR, Brazil

M Felicetti
Fire Risk Analysis Laboratory, Federal University of Ouro Preto, Ouro Preto, MG, Brazil

Abstract
Fires are frequent in urban slums. In general, a fire beginning in a slum community gets out of control and the resultant fire propagation affects large areas. Lack of reliable data on slum fires is an obstacle for immediate application of quantitative methods for fire risk assessment. This article proposes an evolutionary approach to risk assessment in slums. The concepts of structured and unstructured systems for risk assessment are introduced. A sequence of methods is proposed going from qualitative to fully quantitative. In addition, a critical analysis of the index method is provided; such a method might avoid subjectivity in adopting a power rule for risk and safety factors.

Keywords
Urban slums, structured and unstructured systems, risk assessment, index methods

Introduction

Precarious urban settlements are common on the outskirts of large Brazilian cities. They are called 'favelas' (slums) and are the consequence of a complex urbanization process that became most evident in the second half of the twentieth century with the start of industrialization and urban migration [1]. As one of the impacts of accelerated

Corresponding author:
AM Claret, Fire Risk Analysis Laboratory, Federal University of Ouro Preto, Ouro Preto, MG, Brazil
Email: claretgouveia@uol.com.br

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urbanization, the increase in precarious habitats generated high-level fire risk situations. In the City of Sao Paulo, more than one million people live in 'favelas' [2].

Although frequent, there are no available official statistics on fires that have occurred in slums in Brazil. Newspaper reports of fires in slums in the Metropolitan Sao Paulo area during a 24-month period can give some idea of their frequency and social repercussions (see Table 1). There are only a very few studies concerning fire risk in slums in Brazil [3] although nowadays social, political, and economic scientists have been investigating [4] these complex communities.

This article proposes an evolutionary approach to fire risk assessment in Brazilian slums. It is suggested that fire risk assessment in slums must start with qualitative methods [5], gradually creating a database for future application of semi-quantitative and fully quantitative probabilistic methods. The concepts of structured and unstructured systems are introduced to justify the need for such an evolutionary approach. As the proposed approach begins with application of an index method, a discussion of its alleged subjectivity is provided.

It must be added that slums are common throughout Latin and Central America as well as in Asiatic countries with the same characteristics [6]. Thus, although developed for the Brazilian 'favelas,' the proposed evolutionary approach is in principle applicable to precarious urban settlements in other countries.

Background

Slum fire risk assessment challenges fire protection engineers with two paradoxes. Firstly, although socially very complex [4], these systems are very simple from the

Table 1. Slum fires in Metropolitan Sao Paulo, in a 24-month period.

Date	Slum name	Destroyed shacks
30/01/2011	Serra Pelada	30
06/12/2010	Vila Maria	06
26/08/2010	Jardim Sao Francisco	Not informed
19/05/2010	Naval	100
16/01/2010	Mundo Novo	Not informed
19/12/2009	Jabaquara	60
06/12/2009	Agua Espraiada	250
02/11/2009	Paraisopolis	10
11/10/2009	Jaguare	300
09/10/2009	Imigrantes	4
16/08/2009	Guaianases	Not informed
26/06/2009	Jabaquara	5
01/05/2009	Moinho	Not informed
17/04/2009	Billings-Jaguara	50

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point of view of risk estimation in the face of an extreme vulnerability to fire. Experience has shown that, in general, fires in slums are very destructive, causing significant property losses (see Table 1). Deaths and injuries occur, mainly involving children, elderly, disabled people, and drug and alcohol users. Secondly, in spite of slums being an extremely vulnerable system without a real chance to be part of any governmental program of re-urbanization in a short period of time, risk assessment in Brazilian slums will probably not change, although attempts will be made to reduce the level of fire risk inherent in slums.

External context for risk assessment

There is clear evidence that the frequency of slum fires is associated with the low socio-economical and cultural level of the affected population [2]. Brazilian government action in slums has been associated with social programs that aim to protect the environment and defend human rights, such as health, nutrition, and basic education. However, these actions do not specifically aim to reduce fire hazards. But, the frequency and destructive effects of slum-fires are not ignored by all sectors of society. Community and nongovernmental organizations take upon themselves the task of acting to reduce communities' vulnerability to fire. Nevertheless, these organizations cannot undertake programs of slum urbanization, but they can take care of dweller's education for fire prevention, organize community fire brigades, and install low-cost fire safety equipment. In this endeavor, the proposed evolutionary approach for slum fire risk assessment aims to guide the interventions and measure its progress over the years.

Internal context for risk assessment

The internal context [5] for risk assessment is marked by illegal land tenure, inordinate space occupation, and lack of urban infrastructure. Some slums develop through land invasion near urban centers and are characterized by heterogeneous division of lots and public spaces, making it extremely difficult to install urban infrastructure; others are in areas destined for the construction of public housing settlements and to some extent preserve the layout of streets and squares. In both cases, the buildings are precarious, poorly ventilated, and frequently have internal and external finishing that is highly combustible. Locally, these buildings are called 'barracos' (shacks) and have a floor space of somewhere between 30 and 60 m^2 [3].

Slum-dwellers are not willing to move to other urbanized areas because slums are in general well-located near industries, better villages, commerce, and other urban services. Thus, if a fire destroys a set of shacks they will be rebuilt very quickly as the lot must always be occupied or it will be lost. It is unlikely that the new building will adopt fire prevention measures. On the contrary, it is likely that the new building will be more precarious than the previous one.

Lots in slums are irregular and very small and shacks are close to each other. A shack is likely to be surrounded by four other shacks not more than 1 m apart. The demand for new places for the growing family is satisfied in general by the

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invasion of small public spaces. Thus, access by fire brigade equipment is very difficult in slums. To worsen this situation, illegal electricity connections are very common, with energy cables distributed everywhere.

Fire load density in slums tends to be high in the face of reduced floor area of buildings, a relatively high number of users, and high fixed fire load. Furthermore, materials used in shack construction are frequently recycled from other previous usage, often being pieces of cardboard, plastics, and wood. Over the years, depending on the existence of economic resources, shack owners will change walls to masonry, timber roofs to concrete slabs, all while preserving the irregular boundaries of the lot.

Natural barriers for fires in slums are road crossings, water streams, and empty spaces. Frequently, the land is hilly and a stone wall or an uneven terrain may act as a fire barrier. But, if a fire starts, it will be extinguished by fire brigade action or it will propagate up to a natural barrier, leaving behind a scene of destruction. The lack of infrastructure in slums includes the absence of hydrants and no water reserve for fire-fighting brigades, which must come with water trucks. In several cases, considering access restrictions, fire brigades are likely to reach the fire very late.

Event tree analysis

Figure 1 is an example of an event tree model for a fire scenario analysis of slums. Scenarios are described in Table 2. These scenarios are supported by the external and internal context described above. It is seen that due to the high vulnerability of slums, the time taken by fire brigades to arrive becomes the most important factor to define the further state of systems. There is reference made to the time needed to

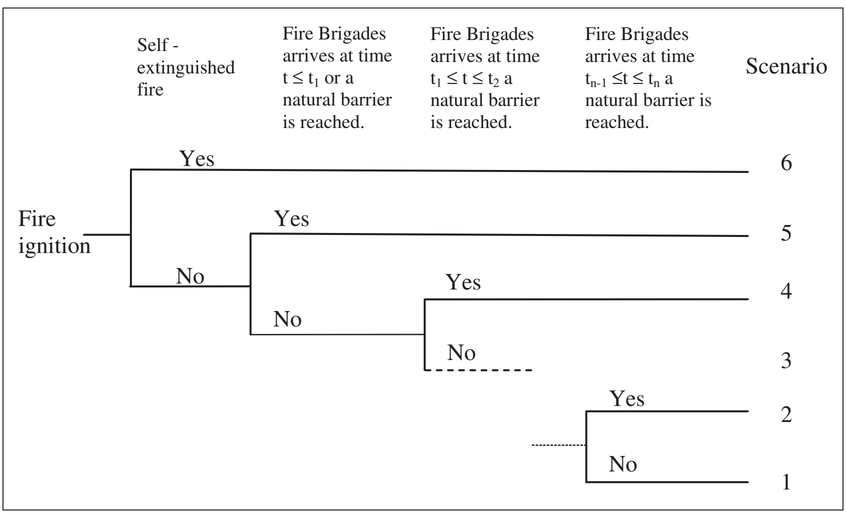

Figure 1. Time-dependent event tree for fire scenario analysis in slums.

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Table 2. Fire scenarios in slums.

Scenario	Description	Time
1	Fire involves and destroys at least 4^n buildings.	t_n
2	Fire involves and destroys at least 4^{n-1} buildings.	t_{n-1}
3	Fire involves and destroys at least 16 buildings.	t_2
4	Fire involves and destroys at least 4 buildings.	t_1
5	Fire develops in the compartment of origin and it is extinguished before outside propagation.	t_o
6	Self-extinguished fire	-

have established burning [7] in some slum building. In Table 2, time t_n is the time needed to burn out 4^n buildings, 4 being the number of neighboring buildings for the building of fire origin in the worst case.

What is new in this event tree model is the fact that fire must be considered as self-extinguished or extinguished by the fire brigade, depending upon the time interval taken to alarm the fire brigades and on access conditions. No automatic alarm or fire suppression may be considered nor the containment of fire within the building or in one compartment. Times t_n depend upon access, size, and nature of the fire load. Although simple, this event tree is an expression of the high vulnerability of slum buildings.

An evolutionary approach

ISO/IEC Standard 31010:2009 [5] classifies methods for risk analyses as qualitative, semi-quantitative, or quantitative, the degree of detail required being dependent upon the particular application, the availability of reliable data and the decision-making needs of the organization. When it comes to apply risk assessment to Brazilian slums, no reliable data referring to fire occurrences is now available. On the other hand, community and nongovernmental interventions, while not a true re-urbanization process, have the challenge of reducing the occurrence of fires, but with no possibility of support from re-urbanization activities. Thus, risk assessment process must consider slums in the first phase of an evolutionary approach for treating unstructured (not purposely designed) systems, as discussed below.

When applying a risk assessment process in developing countries like Brazil, it is useful to distinguish between structured and unstructured systems. Structured systems are designed for a specific answer or behavior – the system objective; unstructured systems are not 'designed' in a sense that they are not built obeying technical standards. Using the concept of system vulnerability [8], unstructured systems may have a high level of susceptibility to accident perturbations, such as fires, inundations, and land-slides. The system is said to be 'unstructured' because the negative consequences are likely huge even for small perturbations in the face of system weakness or instability.

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In structured systems, although admitting the likelihood of deviations from the desired system response or behavior with the production of negative consequences, it is possible to rationally establish a set of system trajectories considering different levels of perturbations as main risk variables. In unstructured systems, the description of accident paths or *risk scenarios* [9] is extremely difficult as it is not rationally possible to wait for a designed response of the system. Thus, it is concluded that it is hard to apply quantitative risk analysis methods to Brazilian slums as they are in their initial stage.

Due to extreme vulnerability, the fire risk in slums is mainly controlled by the presence of hazard and activation parameters, suggesting that an index method must be used in risk assessment. In this class of methods, hazards are ranked according to a scoring system [10]. The Gretener Method [11] and Nelson's Method [7] are cited [10] among the most used index methods, although they differ in nature because Nelson's method includes probabilistic assessment of its components [7] and the Gretener Method is subjective and experience-based.

The index approach is rightly criticized to be 'hazard-centric' [9]. In fact, nowadays it is generally recognized that the scenario approach is frequently more appropriate for risk and vulnerability analysis, although some index methods continue to be implemented in the context of very particular applications [12].

The basic assumption in the proposed evolutionary approach (see Figure 2) is that fire safety could improve with time through progressive and continuous targeted actions. An index method must be used at the start; semi-quantitative and quantitative probabilistic risk assessment methods may be progressively introduced in the evolutionary approach as the system continually evolves from an unstructured to a structured stage. A community association or a nongovernmental organization might take as one of its responsibilities the fire risk watch of the slum.

It is seen that the evolutionary approach is in fact a combination of methods for fire risk assessment of slums. Focusing on an agenda of actions in this first phase,

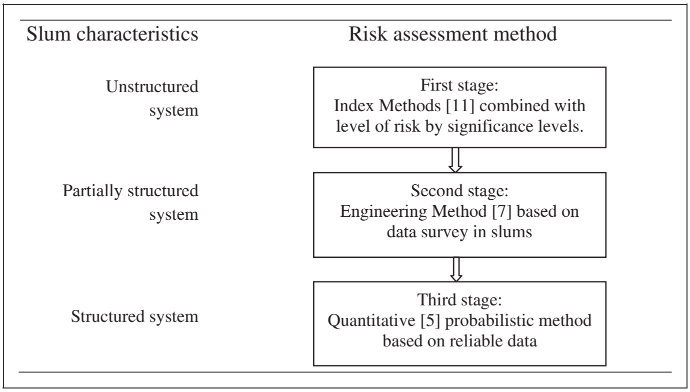

Figure 2. Evolutionary approach for fire risk assessment in slums.

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the lack of fire safety education must come in first place, since it is relatively easy to implement training courses on prevention, evacuation, and the attack of initial fires. Reducing fire load density, removing illegal electrical connections, installing a manual alarm system, constructing water storage tanks, and organizing community fire brigades at least for initial fire-fighting are measures that require relatively low costs. After implementation of these safety measures, the slum is on a second phase, where engineering methods can be used based on surveyed data. Afterward, progressively more changes can be made in the slum space, creating access for fire brigades, removing some dangerous storage buildings, and installing public hydrant systems. At the end, inhabitants must have a culture of fire safety, being capable of reacting to a fire threat. Then, probabilistic risk assessment can be applied.

Criticism of index methods

As noted above, the use of an index method is needed in the first phase of an evolutionary approach. The index approach is criticized in some circles [9,10], who argue that risk scores are established subjectively. ISO/IEC 31010:2009 [5] establishes that methods for fire risk assessment must be (a) logical, (b) systematic, (c) structured, and (d) probabilistic, ensuring a satisfactory level of professional consensus and being fully integrated with the other components of the risk management process. Except for characteristic (d), index methods – although scoring risk levels by technical consensus – are consistent with this standard.

Essentials of index methods

Fire Risk Index (FRI) methods are based on sets of risk and safety parameters associated respectively with risk and safety factors. Both sets of parameters are selected by a group of analysts based on their experience. Actually, these parameter sets are seen as 'opposites.' The first acts to increase the development and propagation of a building fire and the second acts to inhibit the fire. This opposition is similar to a static balance of forces which can be considered the main imperfection of the method. Risk and safety factors are measures of these opposite 'forces' and as a consequence they have a deterministic nature.

The only probabilistic aspect of the FRI method is taken into account through the introduction of an activation factor for the static risk parameters: being 'statically' present in the system, they have to be 'put in action' by some 'dynamic factor' whose nature is clearly random. Safety parameters, on the other hand, are considered always operational, so it is not necessary to introduce safety activation factors. Hence, FRI cannot be considered a measure of the probability of occurrence of a severe fire in the system. In fact, FRI is defined similar to the safety coefficient of the classic admissible stress method in structural analysis.

To properly define FRI, consider a system where the overall risk, F, overall safety, S, and set of risk activation parameters, U, are identified. Here, f_i, S_r, and A_u

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are the individual risk, safety, and activation factors, respectively. Now, FRI can be defined as

$$FRI = \gamma = \frac{\left(\prod_1^F f_i\right)\left(\prod_1^U A_u\right)}{\prod_1^S s_r} \tag{1}$$

where $1/\gamma$ is a fire safety coefficient. As the individual factors f_i, s_r, and A_u are chosen *a priori* in each proposed index method, analyses of a system by different methods are not comparable and neither are analyses of a system by different analysts using a given method. This comparability would be strongly desirable when establishing an evolutionary approach for fire risk assessment involving various slum sets.

In practical terms, risk factors are established by technical consensus of a group of professionals who understand the system behavior. In Brazil, an experienced firefighter officer can have dozens of fire combat experiences in slums before participating in a group of technical consensus sessions. The fact is that the number of slums in a big Brazilian city is large, as is the number of slum fire occurrences. Moreover, after the occurrence of a fire, the people affected immediately return to the same place and rebuild the shacks in the same way, thus preparing a repetition of the phenomenon. Ironically, a fire official will have the opportunity to observe an actual fire more than once in the same slum. As an illustration, Table 3 shows fire events registered during a period of 5 years in a place named 'Favela Jaguare,' southeast of Sao Paulo, Brazil.

Some theoretical bounds can be provided for index methods to reduce subjectivity in the context of an evolutionary approach. Consider index methods where risk, safety, and activation factors are established according to a power rule given by

$$f_{ij} = F_i a^{(j-1)} \tag{2}$$

$$s_{rs} = S_r b^{(s-1)} \tag{3}$$

$$A_{uv} = A_u C^{(v-1)} \tag{4}$$

Table 3. Fires events in Favela Jaguare during a 5-year period.

Date	Destroyed shacks
08/31/2010	20
10/11/2009	350
04/18/2009	24
01/18/2006	50
10/14/2005	3

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where f_{ij} is the risk factor attributed to risk parameter i being $j \in \{1,2,...F\}$ the score chosen to evaluate the influence of f_i in generating a severe fire in the actual state of a system; s_{rs} is the safety factor associated with the safety measure s_r existing in the system being $s \in \{1,2,...S\}$ the score chosen to evaluate the power of s_r in inhibiting a severe fire in the actual state of a system; A_{uv} is the activation factor u being $v \in \{1,2,...V\}$ the score chosen to evaluate its power to begin a fire in the actual state of the system. F_i, S_r and A_u are scale factors and the power basis a, u, c are positive numbers. These power rules may be adequate because choosing the proper values of scale factors and power basis, a variety of measures of risk, safety, and activation factor can be generated according to the personal evaluation of the analyst.

It is possible to demonstrate that FRI of a system found through two different analyses are related in a convenient manner according to the subjectivity influence of each analyst. For simplicity, consider that two analysts have chosen the same values for all risk, security, and activation factors, except for risk factor f_i in which they have chosen scores j and l. Thus, for the corresponding FRI, γ_1 and γ_2, one has the following:

$$\gamma_1 \sim F_i a^{(j-1)} \tag{5}$$

$$\gamma_2 \sim F_i a^{(l-1)} \tag{6}$$

As a consequence,

$$\frac{\gamma_1}{\gamma_2} = a^{(j-l)} \tag{7}$$

Except for the possibility of a gross error, it is likely that $j \approx l$ and it will follow that $\gamma_1 \approx \gamma_2$. Otherwise, if there is not a technical consensus about levels j and l, other analyses should be made and the average value of FRI may be adopted. If the analysts disagree in several factors, analogous expressions will be found as the method involves only power products.

Consider now two different methods applied to the analysis of the same system, the parameters f_i and g_k being the only ones different among them. Thus, analyzing one system with these two methods, the same analyst chooses by the first method the score j for the parameter f_i and the score l for the parameter g_k. The FRI will be proportional in the methods 1 and 2, respectively, to

$$\gamma_1 \sim F_i a^{(j-1)} \tag{8}$$

$$\gamma_2 \sim G_k b^{(l-1)} \tag{9}$$

Thus:

$$\frac{\gamma_1}{\gamma_2} = \left(\frac{bF_i}{aG_k}\right)\frac{a^j}{b^l} \tag{10}$$

It is seen in Equation (10) that the expression $\frac{bFi}{aG_k}$ is due only to the difference between methods and that $\frac{a^j}{b^l}$ includes both the influence of the method and of the

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distinct system evaluation with those methods. It is likely that $j \approx l$ as the same analyst is doing both analyses and in this case it is easy to show that

$$\frac{\gamma_1}{\gamma_2} = \left(\frac{bF_i}{aG_k}\right) \exp\left(\frac{\ln a}{\ln b}\right) \tag{11}$$

which is the scale factor between the FRIs of the same system evaluated by two different methods.

Conclusion

In Brazil, slums involve millions of people and have persisted for many decades as a social problem. Slum urbanization is known to be extremely difficult and expensive. As such, government intervention has tended to provide only a minimum of public services. Fire safety is not always included in this minimum in the face of safety, access, housing, health, and sanitation needs. For this reason, community and nongovernmental organizations are induced to act to provide at least a minimum level of fire safety.

Slums are unstructured systems not designed for a specific response to fire. Thus, immediate application of fully quantitative methods or semi-quantitative methods of fire risk assessment to slums is impossible since essential statistical data are lacking. An evolutionary approach for fire risk assessment in Brazilian slums is proposed. Initially, an index method can be adopted. To reduce the subjectivity of this method, a power-based system is suggested.

By adopting a single power-based index method, it is easy to demonstrate that the resultant FRIs from two different analysts will be nearly identical, with the average value representative of the FRI of the system. In the case of one analyst using two different power index methods applied to a known system, a FRI scale factor allows the result from one method to be reduced to the other.

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