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Constructal design of evacuation from a three-dimensional living space

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HIGHLIGHTS

- The fundamental relation between the configuration of a building and the evacuation time needed by all the inhabitants.
- Evacuation of inhabitants is treated as a physical flow system.
- The optimal floor shape and profile shape are reported.
- The theoretical predictions are validated by extensive numerical simulations of pedestrian flow.

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ABSTRACT

This paper demonstrates the fundamental relation that exists between the configuration of a three-dimensional living space and the time needed for the evacuation of all the inhabitants. The evacuation is treated as a physical flow system consisting of pedestrians who move from a volume to one or two exits. The living space has two variable aspect ratios, the floor shape and the profile shape (or the number of floors). First, the paper reports analytically the optimal floor and profile shapes for which the total evacuation time is minimum. Second, the analytical results are complemented and validated by numerical results obtained based on numerous simulations of pedestrian flow from volume to exits. The numerical results are further validated by performing the simulations of pedestrian movement with two different computational codes (Simulex and FDS + Evac). The fundamental relation presented in this paper can be used in the design of larger and more complex living spaces in modern urban settings.

1. Introduction

Self-organization is the backbone of phenomena of design in nature, and it covers the range from geophysics to biology, from inanimate to animate flow systems. Reviews of the current literature show that this part of physics is covered by the constructal law [1,2], which accounts for the natural tendency toward evolutionary design over time (organization, configuration, architecture) that provides greater and easier access in all flow systems that are free to morph.

The evolutionary design tendency is most familiar to us in the flow systems that surround and connect us: transportation, crowd dynamics, business, economics and government. The flow designs that will rule urban design as population density

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continues to increase is crowd movement [1–10], the practical aspect of which is urban design [11–13] and crowd evacuation [14–19]. Urban design expands not only inward, toward high density, but also vertically, above and below ground.

Crowd evacuation is a major concern in a future with "sustainability", and, as in Refs. [1–11], in the present paper we treat it as *physics*. We rely on the constructal law in order to discover the most basic features of a three-dimensional living space (edifice above ground, or underground, e.g., subway station) such that all the inhabitants find easiest access to the outside in case of emergency.

The usual method for the search of building architectures that offer faster evacuation during emergency is based on voluminous numerical simulations of randomly moving pedestrians who pursue the same goal, which is to escape. This paper demonstrates that the search is accelerated significantly when it is based on the method of constructal design, which consists of discovering the fundamental relationship between global flow access and organization—the system configuration when the configuration morphs freely. The present paper identifies analytically the main geometric features of the three dimensional space that offers the shortest evacuation time for all the people present at the start of the emergency. The main features are the floor aspect ratio, and the aspect ratio of the vertical profile of the building. These two features are confirmed based on extensive numerical simulations of pedestrian evacuation, by using two different numerical packages, FDS and Simulex.

The literature on emergency evacuation [19] is extensive and illustrates the critical importance of developing a fundamental basis for designs that facilitate evacuation. For example, the flow of pedestrians based on the size and shape of occupants, queuing in enclosures, flow speed, and passage width was studied by Fruin [16]. Studies focused on keeping pedestrians speeds and directions related to each other in moving along stairways and across horizontal surfaces.

Effective width by including the edge influence of the walkways was suggested for design [20]. The effective width must be reduced by 0.46 m on each side for corridors based on the field survey. The edge effect depends on the activities of the individuals and types of enclosures. However, this concept was not applied to stair movement because more variables are involved. Estimation for vertical movement would be more complicated than that along horizontal surfaces. Speeds attained by occupants depend on the physical dimensions of the stairway, such as stairway angle, tread depth, riser heights, and handrails. Occupant movement would be slower in an enclosed stairwell because the population density changes along the way to give rise to bottlenecks and blockages.

Systematic and detailed observations of evacuation drills in tall buildings were reported in the literature [21–25]. The concept of "edge gap" was further extended to develop an effective width model [22,24]. Taking into account the human propensity to maintain a separation from stationary objects and walls, calculations based only on the "unit width" alone are not accurate if the crowd density is not high. The same conclusion applies to staircase movement. The speed down the stairs is related to the crowd density. Field studies on stairs flow rates in 29 drills in tall buildings [22,24] suggested that the edge effect was 0.3 m. A speed–density relation in uncontrolled total evacuations of tall office buildings was deduced by Pauls [21].

Useful for design are the results reported by Polus et al. [22] and Ando et al. [23]. One- and three-regime speed–density models for the pedestrian traffic were developed [22] based on survey studies in the central business district of Haifa. The walking speed of the pedestrian was found to decrease significantly with increasing density, and the walking speeds of men were significantly greater than the speeds of women. Based on the analysis of speed and density, four levels of services for pedestrians were defined and reported. Organized crowd movement is a common feature in dense railway stations [23], and it was documented with video recordings. Passengers did not know that their movements were recorded. Walking speeds were confirmed to depend on crowd density as proposed by Predtechenskii and Milinskii [26]. The relationship between speed and density, both on a level surface and up and down flights of stairs was also presented. Results were converted into volume flow rates by Smith [24] for convenience in justifying the flow rates along passageways, up and down stairs, and through gates.

Pedestrian speed/flow curves were worked out for six main features encountered in the underground system by Annesley et al. [25]. Investigated were passageways, stairways, escalators, concourses, junctions of passageways, and the platform. Based on the data collected from the survey at a number of locations in the London Underground, the curves were improved by Daly et al. [27] for better estimating pedestrian flow and travel times under congested conditions.

Correlations of velocity for mobile individuals were proposed by Nelson and Mowrer [28] by reviewing the results reported in the literature. A model on the movement of individual occupants was developed by Thompson and Marchant [15] based on the inter-personal distance (not on occupant density). The result was derived by analyzing videos of crowd movement. The inter-personal distance is a measure of distance between the center points of the bodies of two individuals. The relationship between the walking speed and inter-personal distance was presented. The median values were fitted from the surveyed data. The age-weighted values are based on a combination of the median values and the data quoted by Ando et al. [23] for normal, unimpeded walking speeds. The walking speed would decrease when the inter-person distance is less than a specific value, which becomes zero when the individuals are tightly packed. The inter-personal distance is equal to the body width. The interface threshold was suggested to be 1.6 m. When the separation between individuals is greater than this value, their speed is not affected. The unimpeded walking speed was found to be around 1.7 m s^{-1} for men and 0.8 m s^{-1} for women.

Data on downstairs movement in three multiple occupancy buildings were reported by Proulx [29]. The stairway movement was found to involve several features of behavior such as resting and communication. Most of the occupants showed a comparable mean speed on the stairs during the emergency drills. Among all occupants, the travel speed was between 0.52 and 0.62 m s^{-1} on non-crowded stairs. Those older than 65 moved significantly slower, at 0.43 m s^{-1}, and children between