On Modeling Building Evacuation Route Plans by Resorting to P-graph

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Abstract

This paper presents basic ideas on the application of the P-graph framework for modeling building evacuation routes and computing the optimal one. To do so, P-graph relies on both combinatorial and graph techniques for facilitating such a work.

Keywords: Building Evacuation Route Planning, Process Network Synthesis, P-graph Framework.

1 Introduction

Route Evacuation Planning is the science of ensuring the safest and most efficient evacuation time of all expected residents of a building, city or region, or transportation carriers (e.g., train, ship, and airplane) from a treat or actual occurrence of a hazard (e.g., natural disasters, traffic, industrial, or nuclear accidents, fire, viral outbreak, etc.) [1]. In any scenario (i.e., building, city or region, or transportation carriers), a proper planning may imply the evaluation of a countless number of evacuation routes which is considerably challenging because of the combinatorial nature of the problem [2].

In the particular case of building evacuation, the ocuppants' evacuantion is one of the most important concepts of the buildings safety. For this reason, buildings are safe if the are built according to local building authority regulations and codes of practice. However, it is not always necessary to evacuate a building during an emergency. For instance, a power outage does not necessarilly call for an evacuation [3].

The aim of this paper is to introduce P-graph. P-graph is a mathematical framework that may be used to tackle down the inherent complexity of computing the safest and most efficient building evacuation routes. This paper is organized as follows. Section 2 introducte the current state of the art regarding the problem of

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building evacuation route planning. Section 3 briefly describes the P-graph framework. In Section 4, a couple of extension to the P-graph are proposed for dealing with the problem of computing building evacuation routes. Finally, conclusions are drawn.

2 State of the Art

Research in the Building Evacuation Route Planning field fall into six categories[2][4,5]: (i) Level of Service, (ii) Mathematical Models, (iii) Heuristics Methods, (iv) Sthocastics Models, (v) Simulation tools; and, (vi) Multiagent Systems.

In the Level of Service category, research is being focused on characterizing the walking speed and spacing between evacuees based on the density of evacuees using a pathway or corridor [6,7,8,9,10,11,12,13,14,15]. On the other hand, mathematical models look for generating optimal evacuation plans which minimize the total evacuation time. They adopt flow networks algorithms to evaluate the routes (e.g., minimum cost flow, maximum flow, quickest path, etc.). Even though these evacuations planning algorithms generate optimal plans, they are computationally expensive with respect to the resources they can use (e.g., memory and processing time)[16,1]. For example, Francis, in [17,18], proposes the application of mathematical optimization for building evacuation by adopting Brown´s algorithm [19]. Then, Berlin points out the use of flow networks in building evacuation [20] followed by Francis *et al*'s works [21,22]. These works are later on extended to consider problems where flow networks are constrained by their capacities and solved by adopting greedy and polynomial algorithms [23,24,25]. Most recent work is focused on formulating the building evacuation as a multibjective problem ([26,27,28,29,30]) .

The adoption of heuristic methods for solving the building evacuation problem is presented in [31,32] . Although heuristics methods do not always generate optimal evacuation routes, they have been able to reduce the computational cost of the process dramatically. Stochastic approached also has been studied. Althought sticastic models capture the overall egress process more realistically, their resolution is more laborious [33,34,35,36].

In recent years, simulation methods have gained adepts. Simulation methods model and emulate traffic flow and assume that the behavior of individuals is under the influence of other. Three approaches have been adopted for simulating traffic flow[1]: probabilistic models [37,36], cellular automata [38,39,40,41,42],

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[2] In most of the cases, these categories take advantage of the advances in the Geographical Information Systems field for accessing data or drawing graphical location-based information [17].

and multiagent systems [43,44,45,46]. In [47], a list of simulation models and sofware packages for simulating pedestrian motion can be found.

3 Process Network Synthesis

In a process system, raw materials are consumed through various transformations (e.g., chemical, physical, and biological) to desired products. Vessels where these transformations take place are called operating units of the process. A given set of operating units with likely interconnections can be portrayed as a network.

The desired products can be also manufactured via some sub-networks of the above-mentioned network. Thus, a given network may give rise to a variety of processes, or process networks, producing the desired products, and each of such process networks corresponds to a sub-network, that can be considered regarded as its structure. Energy and raw material consumption strongly depend on the selection of a process structure; thus, the optimal design of such a process structure, i.e., the process network synthesis (PNS), or process synthesis in short, has both environmental and economic implications [48].

A number of methods has been developed for process synthesis [49]. These methods can be classified according to whether they are based on heuristics or algorithms, i.e., mathematical programming approaches. The majority, if not all, of these methods, however, may not be sufficiently effective for PNS of a realistic, or industrial scale, process because of its combinatorial complexity arising from the involvement of a large number of interconnected loops [48]. To cope with this, an innovative approach based on P-graphs (process graphs), which are unique, mathematically rigorous bipartite graphs, has been proposed to facilitate the process network synthesis [50]. The P-graphs are capable of capturing not only the syntactic but also semantic contents of a process network. Subsequently, an axiom system underlying the P-graph framework is constructed to define the combinatorial feasible process-network structures. The analysis and optimization of properties of such structures are performed by a set of efficient combinatorial algorithms: MSG [51], SSG [51], and ABB [52].

3.1 Process Graph (P-graph)

The mathematical definition of a P-graph and a process structure represented by it are elaborated below [50].

Finite set M, containing materials, and finite set O, containing operating units, are given such that

$$O \subseteq \wp(M) \text{ x } \wp(M) \tag{1}$$

Thus, a P-graph can be defined to be a pair, (*M*, *O*), as follows:

(i) The vertices of the graph are the elements of

$$V = M \times O \qquad (2)$$

Those belonging to set *M* are of the M-type vertices, and those belonging to set *O* are of O-type vertices.

(ii) The arcs of the graph are the elements of

$$A = A_1 \cup A_2 \qquad (3)$$

where

$$A_1 = \{(X,Y) \mid Y = (\alpha,\beta) \in O \text{ and } X \in \alpha\} \qquad (4)$$

and

$$A_2 = \{(Y,X) \mid Y = (\alpha,\beta) \in O \text{ and } X \in \beta\} \qquad (5)$$

In these expressions, X designates an M-type vertex; Y, an O-type vertex; α a set of M-type vertices from which arcs are directed into the O-type vertices; and, β a set of M-type vertices to which arcs are directed out of the O-type vertices.

For illustration let M be a set of materials, $M = \{A,B,C,D,E,F\}$, and O be a set of operating units given by $O = \{(\{B,A\}, \{A\}), (\{D,E\}, \{B,C\}), (\{F\}, \{A,C\}), (\{F\}, \{A,C\})\}$. It is not difficult to validate that sets *M* and *O* satisfies constraint (1), i.e., (*M*, *O*) is a P-graph, as depicted in Figure 1.

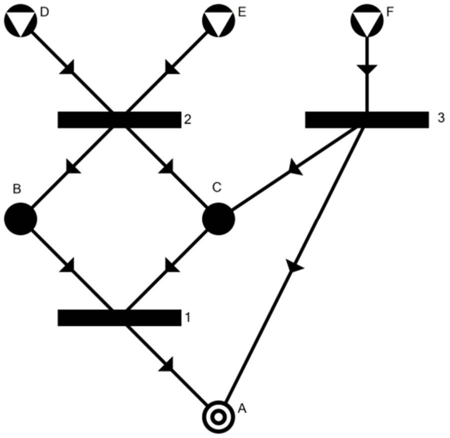

Figure 1. P-graph (*M,O*) where *A,B,C,D,E,* and *F* are materials, and *1,2,* and *3* are the operating units: ▽ represents raw materials or input elements of the whole process; ● symbolizes intermediate-materials or elements, emerging between the operating units; and ◎ represents products or outputs of the entire process.

3.2 Solution Structures

The materials and operating units in a feasible process structure must always conform to certain combinatorial properties. For example, a structure containing no linkage between a raw material and a final product is unlikely to represent any practical process. Hence, it is of vital importance to identify the general combinatorial properties to which a structure must conform. More important, the properties identified should be satisfied by the structure of any feasible solution of the synthesis problem. In other words, those and only those structures satisfying these properties can be feasible structures of a process: no other structures or constraints need to be considered in synthesizing the process.

A set of axioms has been constructed to express necessary and sufficient combinatorial properties to which a feasible process structure should conform. Next, each axiom is stated:

(S1) Every final product is represented in the graph.

(S2) A vertex of the M-type has no input if and only if it represents a raw material.

(S3) Every vertex of the O-type represents an operating unit defined in the synthesis problem.

(S4) Every vertex of the O-type has at least one path leading to a vertex of the M-type representing a final product

(S5) If a vertex of the M-type belongs to the graph, it must be an input to or output from at least one vertex of the O-type in the graph.

If a P-graph of a given synthesis problem, (P, R, O)[3], satisfies theses axioms, it is defined to be a solution-structure of the problem. For example, Figure 1 depicts an example of two solution-structures for synthesis problem (P_1, R_1, O_1) with

$M_1 = \{A,B,C,D,E,F,G,H,I\}$

$P_1 = \{A\}$

$R_1 = \{D,F,H\}$

and

O_1 ={({C}, {A,I}), ({B}, {A,E}), ({D,E}, {B}), ({E,F}, {B}), ({F,G}, {C}),({H,I}, {G})}.

Note that a solution-structure does not necessarily contain all the components defined in the set of materials, e.g., M_1; neither does it necessarily utilize all the components specified in the set of raw materials, e.g., R_1.

Since the final product, A, is presented as an M-type vertex in both Figure 2(a) and (b), axiom (S1) is satisfied by the solution-structures depicted in these figures. Axiom (S2) is satisfied in that vertex F in Figure 2 (a) and vertices F and H in Figure 2 (b) are the only vertices without an input; they represent raw materials. Figure 2 (a) contains two operating units, ({E,F},{B}) and ({B},{A,E}), and Figure 2 (b) contains three operating units ({C},{A,I}), ({F,G},{C}), and ({H,I},{G}); all these operating units are defined in the synthesis problem, thereby satisfying axiom (S3). In conformity with axiom (S4), every vertex of the type O-type in either Figure 2 (a) or (b) does have at least one path leading to vertex A representing the final product. For example, the path in Figure 2 (a), comprising three arcs, namely, (({E,F},{B}),B), (B,({B},{A,E})), and (({B},{A,E}),A), links vertex ({E,F},{B}), representing an operating unit, to vertex A which is the final product. Axiom (S5) is satisfied by virtue of the fact that every vertex of the M-type belonging to the graph of either Figure 2 (a) or (b) is an input to or output from at least one vertex of the O-type in the respective graph. Thus all axioms are satisfied by the structures in Figure 2 (a) or (b). As counterexample, Figure 3 illustrates a P-graph that is not a solution structure of synthesis problem (P_1, R_1, O_1), because axioms (S1), (S2), (S4), and (S5) are not satisfied.

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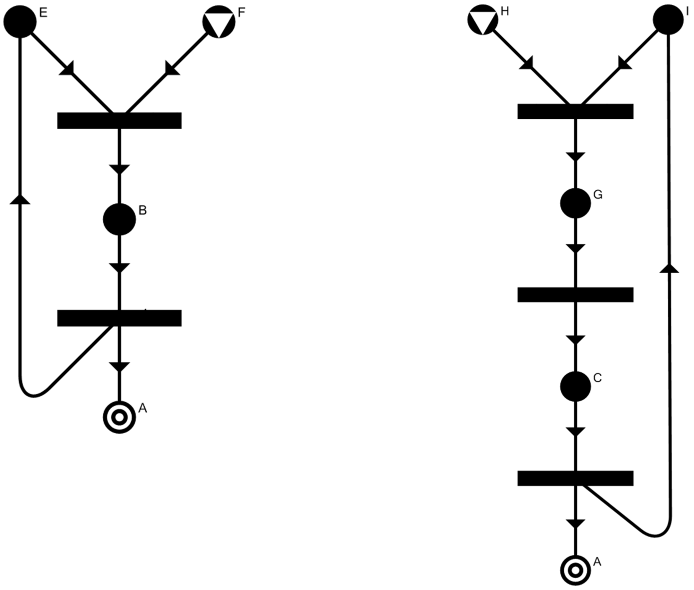
[3] where $P \subseteq M$ is the set of product, $R \subseteq M$ is the set of raw materials, and O the set of operating units



(a)

(b)

Figure 2. Two solution-structures for the synthesis problem *(P_1, R_1, O_1)*

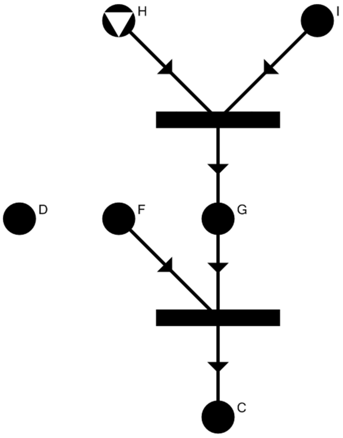


Figure 3. P-graph that is not a solution-structure for synthesis problem *(P_1, R_1, O_1)*

4 P-graph Extensions for Modeling Building Evacuation Routes

In most of cases, building evacuation routes are modeled as network structures [1], a feature that might be exploited by P-graph. However, a couple of extension should be incorporated to P-graph. As presented in Section 3, P-graph is a directed bipartite graph where the vertices are of two types: operating unit type vertex and material type vertex. Material type vertex materials may capture rooms, intersections, and safe areas, as well as their capacity and time to cross along them. Also, operating unit type vertex may capture gates and corridors which are constrained by a flow rate[4]. In addition, operating unit type vertex may act as bottleneck points in the map. The arcs direction between operating units type vertex and material type vertex may be depend upon the hazardous locations and the safe areas.

These features impose new features to be handled in P-graph: dynamic events and spatial graphs. Dynamic events may change the direction of evacuees leaving the building, for example, from the south side to the north side, or from the north side to the west side. The hazardous locations in the building may constraint specific section of the building, therefore, only a section of the graph may be considered in the solution of the problems.

For instance, Figure 5 describes the floor map of a building with nodes (representing rooms, and safe areas) and edges (representing corridors, stairs, and elevators); the location(s) and number of the evacuees(s), the location(s) of the safe area(s), and the hazardous location(s).

Moreover, one remarkable advantages of modeling building evacuation routes by resorting to P-graph relies on its mathematical background which can be applied for computing the optimal network (i.e., evacuation route) [48,51,50,52].

Conclusions

A lot of work has been done in the field of building evacuation route planning (Section 2). However, it is justified to seek for new solution methods because of the combinatorially nature of the problem under consideration. P-graph may be a useful tool for modeling and computing building evacuation routes. As future work, we plan to investigate further applications of P-graph in the field of building evacuation routes.

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[4] A flow rate is the maximum number of people who cross *who move along a* predetermined path or route per unit of time

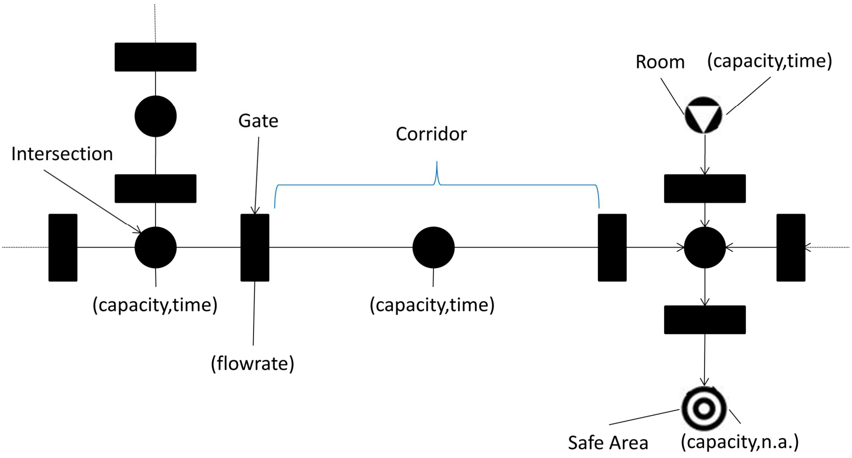

Figure 4

Floor Map Description

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References

[1] H. W. Hamacher and S. A. Tjandra, "Mathematical Modeling of Evacuation Problems: A state of the art," in *Pedestrian and Evacuation Dynamics*.: Springer, 2002, pp. 227-266.

[2] K. Sangho and S. Shashi, "Contraflow network reconfiguration for evacuation planning: a summary of results," in *13th annual ACM international workshop on Geographic information systems (GIS '05)*, Bremen, 2005, pp. 250-259.

[3] R. W. Bukowski, "Emergency Egress From Buildings. Part 1. History and Current Regulations for Egress Systems Design," in *Sky is the Limit. Proceedings and Case Studies.*, Auckland, 2008, pp. 167-191.

[4] S. Casadesús Pursals and F. Garriga Garzon, "Basic Principle for the Solution of the Building Evacuation Problem," *Journal of Industrial Engineering and Management*, vol. 2, no. 3, pp. 499-516, 2009.

[5] E. D. Kuligowski and D. S. Mileti, "Bibliography on Evacuation From Building Fires: Education, Behavior and Simulation Techniques," National Institute of Standards and Technology, Report 2007.

[6] H. J.P Timmermans, *Pedestrian Behavior: Models, Data Collection, and Applications*. London: Emerlad Group Publishing, 2009.

[7] R. D. Peacock, E. D. Kuligowski, and J. D. Averill, Eds., *Pedestrian and Evacuation Dynamics*, 1st ed., 2011.

[8] G. Proulx, A. Kaufman, and J. Pineau, "Evacuation Time and Movement in office Buildings," National research Council Canada, Report 1996.

[9] V. M. Predtechenskii and A. I. Milinskii, *Planning Foot Traffic Flow in Buildings*. New Delhi: Amerind Publishing Co, 1978.

[10] J. L. Pauls, "Movement of People," in *The SPE Handbook of Fire Protection Engineering*., 1996, vol. 3, ch. 12, pp. 263-285.

[11] J. L. Pauls, "The Movement of People in buildings and Design Solutions for Means of Egress," *Fire Technology*, vol. 20, no. 1, p. 27, 1984.

[12] J. L. Pauls and B. K. Jones, "Building Evacuation: Research Methods and Case Studies," *Fires and Human Behavior*, pp. 227-251, 1980.

[13] H. E. Nelson and H. A. McLennan, "Emergency Movement," in *The SPE Handbook of Fire Protecction Engineering*., 1996, vol. 3, ch. 14, pp. 286-295.

[14] Board London Transport, "Secord Report of the Operational Research Team on the Capacity of Footways," London Transport Borad, London, Report 1958.

[15] V. V. Kholshenikov, T. H. Shields, K. E. Boyce, and D. A. Samoshin, "Recent Developments in Pedestrian Flow Theory and Research in Russia," *Fire Safety Journal*, vol. 43, pp. 108-118, 2006.

[16] K. Togawa, "Study of Fire Escae Based on the Observation Multitude currents," Japan Building Research Institute, Report 1955.

[17] R. L. Francis, "A Simple Graphical Procedure to Estimate the Minimum time to Evacuate a Building," Society of Fire Protection Engineers, Report 1979.

[18] R. L. Francis, "A 'Uniformity Principle' for Evacuation Route Allocation ," *Journal of Research of National Bureau of Standards*, no. 86, pp. 509-513.

[19] J. R. Brown, "The Knapsack sharing problem. Operation Research,"

Operation Research, vol. 27, no. 2, pp. 340-355, 1979.

[20] G. N. Berlin, "A Network Analysis of Building Egress System," ORSA/TIMS, Washington, DC, Meeting 1985.

[21] L. G. Chalmet, R. L. Francis, and P. B. Saunders, "Network Models for building Evacuation," *Management Science*, vol. 28, pp. 86-105.

[22] T. M. Kisko and R. L. Francis, *Network Models of Building Evacuation: Development of Software System*, National Technical Information Service, Ed. Washington, DC, 1984.

[23] W. Choi, S. Hamacher, and S. Tufecki, "Modeling of building Evacuation Problems by Network flow with Side Constraints," *Euroepan Journal of Operational Research*, vol. 35, pp. 98-110, 1988.

[24] B. Hope and E. Tardos, "Polynomial Time Algorithms for Some Evacuation Problems," in *Ffifth annual ACM-SIAM symposium on Discrete algorithms (SODA '94)*, 1994, pp. 433-441.

[25] B. Hope and E. Tardos, "The Quickest Transshipment Problem," *Journal of Mathematics of Operations Research*, vol. 25, no. 1, 2006.

[26] M. M. Kostreva, M. M. Wiecek, and T. Getachew, "Optimization Models In Fire Egress Analysis For Residential Buildings," *Fire Safety Science*, vol. 3, pp. 805-814, 1991.

[27] T. Getachew, "An Algorithm for Multiple-objective Path Optimisation with Time Dependant Links," in *10th International Conference on Multicriteria Decision Making*, 1992, pp. 319-330.

[28] T. Getachew, M. Kostreva, and L. Lancaster, "A Generalization of Dynamic for Pareto Optimisation in Dynamic Networks," *RAIRO Operation Research*, vol. 34, pp. 27-47, 2000.

[29] T. Wiecek, "Approximation in Time-dependent Multi-objective Path Planning," in *1992 Conference on Systems, Man, and Cybernetics*, 1992, pp. 861-866.

[30] T. Wiecek, "Multicriteria Decision Making in Fire Egress Analysis," in *IFAC/IFORS Workshop on Support Systems for Decision and Negotiation*, 1992, pp. 285-290.

[31] Q. Lu, Y. Huang, and S. Shekhar, "Evacuation Planning: A Capacity Constrained Routing Approach," in *First NSF/NIJ Symposium on Intelligence and Security Informatics*, 2003, pp. 291-307.

[32] Q. Lu, B. George, and S. Shekhar, "Capacity Constrained Routing Algorithms for Evacuation Planning: A Summary of Results," in *Advances in Spatial and Temporal Databases*, C. Bauzer Medeiros, M. Egenhofer, and E. Bertino, Eds., 2005, pp. 291-307.

[33] J. M. Smith and D. Bakuli, "Resource Allocation in state Dependent Emergency Evacuation Networks," *European Journal of Operation Research*, vol. 89, pp. 543-555.

[34] J. M. Smith and C. J. Karbowicz, "A K-shortest Paths Routing Heuristic for Stochastic Network Evacuation Models," *Engineering Optimization*, vol. 7, pp. 253-280, 1984.

[35] J. M. Smith and K. Talebi, "Stochastic Network Evacuation Models," *Computer & Operation Research*, vol. 12, no. 6, pp. 559-577, 1985.

[36] G. G. Lovas, "Models of Way Finding in Emergency Evacuations," *European Journal of Operation Research*, no. 105, pp. 371-389, 1998.

[37] M. Ebihara, A Ohtsuki, and H Iwaki, "Model For Simulating Human BehaviorDuring Emergency Evacuation Based On Classificatory Reasoning And Certainty Value Handling," *Shimizu Technical Research Bulletin*, no. 11, pp. 27-33, 1992.

[38] V. J. Blue and J. L. Adler, "Using Cellular Automata Microsimulation to Model Pedestrian Movements," in *14th International Symposium on Transportation and TraÆc Theory*, Jerusalem, 1999, pp. 235-254.

[39] S. Benjaafar, K. Dooley, and W. Setyawan, "Cellular Automata for Traffic Flow Modeling," University of Minnesota, Minneapolis, Report 1997.

[40] J. G. Doheny and J. L. Fraser, "MOBEDIC - A Decision Modelling Tool For Emergency Situations," *Expert Systems With Applications*, vol. 10, no. 1, pp. 17-27, 1996.

[41] H. Klupfel, T. M. Konig, J. Wahle, and M. Schreckenbe, "Microscopic Simulation of Evacuation Processes on Passenger Ships," in *Fourth International Conference on Cellular Automata for Research and Industry*, Karlsruhe, 2000.

[42] K. Nagel and M. A. Schreckenberg, "A Cellular Automaton Model for Freeway Traffic," *Journal of Physique I*, vol. 2, pp. 2221-2229, 1999.

[43] J Tsai et al., "ESCAPES: evacuation simulation with children, authorities, parents, emotions, and social comparison," in *The 10th International Conference on Autonomous Agents and Multiagent Systems*, 2011, pp. 457-

464.

[44] N. Ronald, L. Sterling, and M Kirley, "An Agent-based Approach to Modeling Pedestrian Behavior," *International Journal of Simulation Systems, Science & Technology*, vol. 8, 2007.

[45] F. Klugl and G. Rindsfuser, "Large-Scale Agent-Based Pedestrian Simulation," in *5th German conference on Multiagent System Technologies (MATES '07)*, 2007, pp. 145-156.

[46] S. Capri et al., "Agent-Based Simulation of Pedestrian Behaviour ," in *Symposium on Engineered and Natural Complex Systems-Modeling, Simulation and Analysis*, 2009, pp. 79-84.

[47] T. Kretz, "Pedestrian Traffic: Simulations and Experiments," University of Duisburg-Essen, Essen, PhD Dissertation 2007.

[48] F. Friedler, L. T. Fan, and B. Imreh, "Process Network Synthesis: Problem Definition," *Networks*, vol. 28, pp. 119-124, 1998.

[49] M. Minoux, "Networks synthesis and optimum network design problems: Models, solution methods and applications," *Networks*, vol. 19, pp. 313-360, 1989.

[50] F. Friedler, K. Tarján, Y. W. Huang, and L. T. Fan, "Graph-theoretic approach to process synthesis: axioms and theorems," *Chem. Engng. Sci.*, vol. 47, pp. 1972-1988, 1992b.

[51] F. Friedler, K. Tarján, Y. W. Huang, and L. T. Fan, "Combinatorial Algorithms for Process Synthesis," *Computers Chem. Engng.*, vol. 16, pp. S313-320, 1992a.

[52] F. Friedler, J. B. Varga, E. Feher, and L. T. Fan, "Combinatorially Accelerated Branch-and-Bound Method for Solving the MIP Model of Process Network Synthesis," in *In Nonconvex Optimization and Its Applications, State of the Art in Global Optimization, Computational Methods and Applications*, C. A. Floudas and P. M. Pardalos, Eds. Dordrecht: Kluwer Academic Publishers, 1996, pp. 609-626.

[53] M. Miah, "Survey of Data Mining Methods in Emergency," in *Conference for information Systems Applied Research*, vol. 4, Wilmington, 2011.

[54] J.J. Fruins, *Pedestrian Planning and Design*, 1st ed. New york, USA: Metropolitan Association of Urban Designers and Environmental Planners, 1971.

[55] R. L. Francis and T. M. Kisko, "EVACNET+: A Computer Program to

Determine Optimal Building Evacuation Plans," *Fire Safety Journal*, vol. 9, pp. 211-220, 1985.

[56] R. L. Francis and P. B. Saunders, *EVACNET: Prototype Network Optimisation Model for Building Evacuation*.: National Bureau of Standards, 1979.

[57] T. Kisko, R. L. Francis, and C. Nobel, "EVACNET4: User´s Guide," University of Florida, Report 1998.

[58] P. A. Thompson and E. W. Marchant, "A Computer Model for the Evacuation of Large Building Populations," *Fire Safety Journal*, vol. 24, pp. 131-148, 1995.

[59] P. A. Thompson and E. W. Marchant, "Testing and Application of the Computer Model SIMULEX," *Fire Safety Journal*, vol. 24, pp. 149-166, 1995.

[60] E. R. Galea, S. Gwinne, P. Lawrence, and L. Filipidis, "Modeling Occupant Interaction with Fire Conditions using the building EXODUS evacuation Model," *fire Safety Journal*, vol. 36, no. 4, pp. 327-357, 2001.

[61] L. S. Poon, "Evacsim: A Simulation Model Of Occupants With Behavioural Attributes In Emergency Evacuation Of High-rise Building Fires," *Fire Safety Science*, vol. 4, pp. 681-692, 1994.