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 occupants’ 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 necessarily 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 introduce 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


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 multiobjective 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. Although stochastic 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],

\(^2\) 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 software 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

$$O \subseteq \wp(M) \times \wp(M)$$

(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

\[ V = M \times O \]  \hspace{1cm} (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

\[ A = A_1 \cup A_2 \]  \hspace{1cm} (3)

where

\[ A_1 = \{(X,Y) \mid Y = (\alpha, \beta) \in O \text{ and } X \in \alpha\} \]  \hspace{1cm} (4)

and

\[ A_2 = \{(Y,X) \mid Y = (\alpha, \beta) \in O \text{ and } X \in \beta\} \]  \hspace{1cm} (5)

In these expressions, \(X\) designates an M-type vertex; \(Y\), an O-type vertex; \(\alpha\) a set of M-type vertices from which arcs are directed into the O-type vertices; and, \(\beta\) 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.
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, \((P, R, O)\), 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, \(((\{E, F\}, \{B\}), B), B, B, (\{B\}, \{A, E\}\) 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
Figure 2. Two solution-structures for the synthesis problem \((P_1, R_i, O_j)\)

Figure 3. P-graph that is not a solution-structure for synthesis problem \((P_1, R_i, O_j)\)
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.

\(^4\) A flow rate is the maximum number of people who cross who move along a predetermined path or route per unit of time
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References


Figure 4
Floor Map Description


