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Planning Evacuation Routes with the P-graph Framework

Juan C. Garcia-Ojeda*[a], Botond Bertok[b], Ferenc Friedler[b]

[a]Department of Systems Engineering, Autonomous University of Bucaramanga, Bucaramanga, Av. 42 No 48-11, Colombia
[b]Department of Computer Science and Systems Technology, University of Pannonia, Veszprém, Egyetem u.10, H-8200,Hungary
jgarciao@unab.edu.co

The P-graph framework is proven to be highly effective in solving Process Network Synthesis. In the present work, the P-graph framework has been adopted for solving the routing and scheduling of evacuees, facing a life-threatening situation. First the building evacuation problem is represented by means of a P-graph model, which is then transformed into a time-expanded process network synthesis (PNS_T) problem that can be algorithmically handled by the P-graph framework. In the proposed method, each location in the building and their passages are given by a set of attributes to be taken in the evacuation route planning. In addition to the globally optimal solution of the building evacuation problem, the P-graph framework provides the n-best suboptimal solutions, when computational possible. The viability of the proposed model is illustrated by an example.

1. Introduction

The aim of any building evacuation plan is to ensure the safest and fastest movement of individuals away from any threat (e.g., bomb threat, taking of hostages) or the actual occurrence of a hazard (e.g., traffic, industrial, or nuclear accidents; natural disasters, fire, viral outbreak) (Stringfield, 1996). However, currently, buildings are designed taller and more complex than ever before, thus making it difficult to design an effective evacuation plan (Pu and Zlatanova, 2005).
In any emergency scenario, an optimal or near optimal evacuation plan may imply the evaluation of a myriad of evacuation routes which is considerably challenging because of the combinatorial nature of the problem (Cova and Johnson, 2003; Hamacher and Tjandra, 2002; Kim et al., 2008). Also, evacuation plans lack flexibility. That is, evacuation plans follow pre-defined evacuation routes, regardless whatever has happened inside the building. This may lead individuals into dangerous situations (e.g., blocked exits, or spaces with gas leakage) (NFPA, 1996; Pu and Zlatanova, 2005). Optimization software for supporting human decisions is essential to implement the major means mentioned above (Cova and Johnson, 2003; Dimakis et al., 2010; Pu and Zlatanova, 2005). Presented herein is an algorithmic method for calculating the optimal building evacuation route planning supported by software tools at each step.

2. Problem Definition

A P-graph model is defined by two sets, the set O of activities and the set M of entities serving as the preconditions to and outcomes from the activities. For evacuation planning the potential locations of evacuees including safe areas (e.g., rooms, corridors, safe areas, stairs, or intersections) on the building-floor map are represented by entities $m \in M$, and the potential movements between the

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locations (through, e.g., passages, gates, or doorways, and edges) by activities $o \in O$ (see Figure 1 and Figure 2) (Garcia-Ojeda, 2011). We are to minimize the time of a building evacuation plan consisting of a set of evacuation routes and a scheduling of evacuees on each route.

The evacuation plan should observe the constraints imposed by the building itself (Hamacher and Tjandra, 2002). For instance, each location m has a limited capacity expressed by non-negative integer cap_m. That is, the number of individuals staying at it. The initial occupancy is also assigned to each location m by non-negative integer ic_m. That is, the number of individuals located at any given location in the event of an emergency. Similarly, the maximum flow rate of a passage o is defined by positive integer cap_o. The flow rate is the maximum number of individuals can travel through it simultaneously. Passages act as bottleneck points in the floor-map. Finally, each passage o is constrained by non-negative travel time tt_o. Travel time measures how long it takes a person to go from one end of the passage to the other.

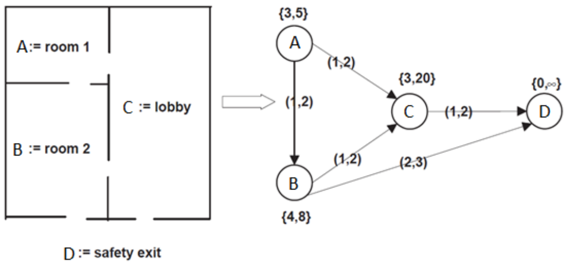

Figure 1: Conventional graph-based notation for representing building floor maps (Hamacher and Tjandra, 2002)

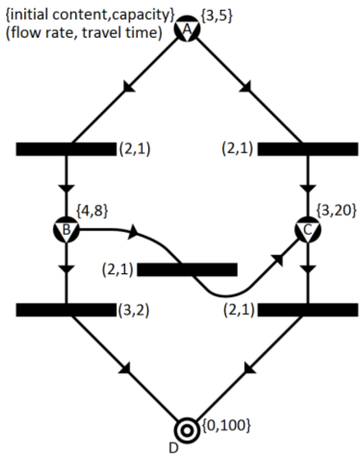

Figure 2: P-graph representation of the building floor map introduced in Figure 1

3. Methodology

The P-graph representation of a building floor map is transformed into the corresponding time-expanded process-network synthesis problem (PNS_T). The P-graph representation of the PNS_T problem provides an easily discernible structural model and the basis for effective solution by combinatorial accelerations as well (Friedler et al., 1992a; Friedler et al., 1993, Friedler et al., 1995, Friedler et al., 1996). The proposed approach ensures that the resultant solution is globally optimal; in addition, it yields the *n*-best feasible scheduling, when computationally possible (Friedler et al., 1996).

Given an upper bound T of the evacuation time and for set M of entities (i.e., locations), a PNS_T problem is given by a triplet (P, R, O), where set P contains the final targets to be reached (i.e., exit points); set R contains the initially available resources (i.e., initial locations of evacuees); and set O, comprises the candidate activities for forming a network to reach each of the final target by moving the total amount of available resources. Each activity o is defined by the pair of its preconditions and outcomes. A precondition can be the availability of a resource or an outcome of another activity.

$\boldsymbol{Input}: M_{input}, O_{input}, T$

$\boldsymbol{Output}: P, R, O$

$M = \emptyset; O = \emptyset; evacuees = 0;$

$Comment: R_{input} \subset M_{input}, P_{input} \subset M_{input}, R_{input} \cap P_{input} = \emptyset, symbol\ |\ |\ represents\ set\ cardi$

$\qquad R \subset M, P \subset M, R \cap P = \emptyset$

$\boldsymbol{begin}$

$\boldsymbol{for\ all}\ m \in R_{input}\ \boldsymbol{do}$

$\quad evacuees = evacuees + ic_m; r = m; U_r = ic_m; L_r = 0; M = M \cup \{r\}; R = R \cup \{r\};$

$\boldsymbol{end\ for}$

$p = \{Exit\};\ U_p = \infty; L_p = evacuees; P = P \cup \{p\};$

$\boldsymbol{for}\ t \leftarrow 0\ to\ T-1\ \boldsymbol{do}$

$\quad \boldsymbol{for\ all}\ m \in M_{input} \backslash P_{input}\ \boldsymbol{do}$

$\qquad M = M \cup \{m\_(t+1)\};$

$\qquad \boldsymbol{if}\ t = 0\ \boldsymbol{then}\ m\_m\_t\_(t+1) = \{\{m\}, \{m\_(t+1)\}\};$

$\qquad\qquad \boldsymbol{else}\ m\_m\_t\_(t+1) = \{\{m\_t\}, \{m\_(t+1)\}\};$

$\qquad \boldsymbol{end\ if}$

$\qquad O = O \cup \{m\_m\_t\_(t+1)\};$

$\qquad U_{m\_m\_t\_(t+1)} = cap_m; L_{m\_m\_t\_(t+1)} = 0; cp_{m\_m\_t\_(t+1)} = 0;$

$\qquad \boldsymbol{for\ all}\ o = (\alpha, \beta) \in O_{input} \setminus \left\{x | x = \bigcup_{(\alpha,\beta) \in O_{input} \wedge m \notin \alpha} (\alpha, \beta)\right\} \boldsymbol{do}$

$\qquad\quad b = \{x | x \in \beta\};$

$\qquad\quad \boldsymbol{if}\ \beta \cap P_{input} = \emptyset$

$\qquad\qquad nm = \{b\_(t + tt_o)\};$

$\qquad\quad \boldsymbol{else\ if}\ |P_{input}| = 1\ \boldsymbol{then}\ e = \{x | x \in \beta\}; nm = \{e\_(t + tt_o)\};$

$\qquad\qquad\qquad \boldsymbol{else}\ e = \{PreExit\};\ nm = \{e\_(t + tt_o)\};$

$\qquad\qquad \boldsymbol{endif}$

$\qquad\qquad \boldsymbol{if}\ t = 0\ \boldsymbol{then}\ m\_b\_t\_(t + tt_o) = \{\{m\}, \{nm\}\};$

$\qquad\qquad\qquad \boldsymbol{else}\ m\_b\_t\_(t + tt_o) = \{\{m\_t\}, \{nm\}\};$

$\qquad\qquad \boldsymbol{end\ if}$

$\qquad\qquad M = M \cup \{nm\}$

$\qquad\qquad O = O \cup \{m\_b\_t\_(t + tt_o)\}; U_{m\_b\_t\_(t+tt_o)} = cap_o; L_{m\_b\_t\_(t+tt_o)} = 0; cp_{m\_b\_t\_(t+tt_o)} = 0;$

$\qquad\quad \boldsymbol{end\ if}$

$\qquad \boldsymbol{end\ for}$

$\quad \boldsymbol{end\ for}$

$\boldsymbol{end\ for}$

$\boldsymbol{for}\ t \leftarrow 1\ to\ T\ \boldsymbol{do}$

$\quad flag = false;$

$\quad \boldsymbol{for\ all}\ p \in P_{input}\ \boldsymbol{do}$

$\qquad \boldsymbol{if} |P_{input}| = 1$

$\qquad\quad \boldsymbol{then}\ M = M \cup \{p\_t\}; evactime\_t = \{\{p\_t\}, \{Exit\}\};$

$\qquad\quad \boldsymbol{else\ if}\ flag! = true$

$\qquad\qquad \boldsymbol{then}\ M = M \cup \{PreExit\_t)\}; evactime\_t = \{\{PreExit\_t\}, \{Exit\}\}; flag = true;$

$\qquad\qquad \boldsymbol{endif}$

$\qquad \boldsymbol{endif}$

$\quad \boldsymbol{endfor}$

$\quad U_{e\_t} = \infty; L_{e\_t} = 0; cp_{e\_t} = t; O = O \cup \{evactime\_t\};$

$\boldsymbol{endfor}$

$\boldsymbol{end}$

Figure 3: Algorithm for transforming a building evacuation problem into the corresponding time-expanded process network synthesis problem

Figure 3 shows the algorithm for constructing the corresponding time-expanded process synthesis problem for a building evacuation problem. It generates three classes of activities. The first class represents the number of evacuees staying at the same location for another unit of time; the second class represents the number of evacuees traveling from location *i* at time *t* to location *j* in time t + λ_{ij} (where λ_{ij} represents the travel time from *i* to *j*); and, the third class represents the number of evacuees reaching a target point in time *t*.
For an upper bound of the evacuation time *T* = 3, Table 1 list the activities generated by the proposed algorithm to be considered in the time-expanded process network synthesis problem for the example. In the P-graph framework, algorithm MSG gives rise to the maximal structure for the PNS_T problem (Friedler et al., 1993). This maximal structure serves as the input to the generation and solution of the mathematical model by algorithm Accelerated Branch-and-Bound (ABB) (Friedler et al., 1996). Figure 4 depicts the maximal structure for the example. Algorithm ABB yields the optimal and the predetermined *n*-best suboptimal schedules. Figure 5 shows the best 4 feasible route schedules for the example. Algorithms MSG and ABB have been executed by software PNS Studio (PNS Studio, 2010).

4. Results and Discussion

Currently, the alternative feasible schedules generated by algorithm ABB are ranked according to a single criterion: the evacuation time. However, there are other criteria that should be adopted in our proposed method (e.g., individual travel and exposure time; time-based risk and evacuation exposure; and, time-space-based risk and evacuation exposure) (Han et al., 2007).
For instance, the total time required to completely evacuate the individuals from all rooms of the building is 3 units of time by any of the solutions. Nonetheless, if solution #1 is compared with solution # 4, the reader can notice that five evacuees would reach exit point D within 2 units of time by employing solution #1, while only two evacuees would reach exit point D within the same time by employing solution #4. This observation shows how important is the trade-off analysis between different evacuation plan designs (Han et al., 2007).

Table 1: Activities to be considered in the time-expanded process network synthesis for the example

Activity	Precondition	Post-condition	Lower Bound	Upper Bound	Cost
A_A_0_1	A	A_1	0	9	0
A_B_0_1	A	B_1	0	2	0
A_C_0_1	A	C_1	0	2	0
B_B_0_1	B	B_1	0	8	0
B_C_0_1	B	C_1	0	2	0
B_D_0_2	B	D_2	0	2	0
C_C_0_1	C	C_1	0	20	0
C_D_0_1	C	D_1	0	2	0
A_A_1_2	A_1	A_2	0	5	0
A_C_1_2	A_1	C_2	0	2	0
B_C_1_2	B_1	C_2	0	2	0
B_D_1_3	B_1	D_3	0	3	0
C_C_1_2	C_2	C_3	0	20	0
C_D_1_2	C_1	D_2	0	2	0
evactime_1	D_1	Exit	0	∞	1
evactime_2	D_2	Exit	0	∞	1
evactime_3	D_3	Exit	0	∞	1

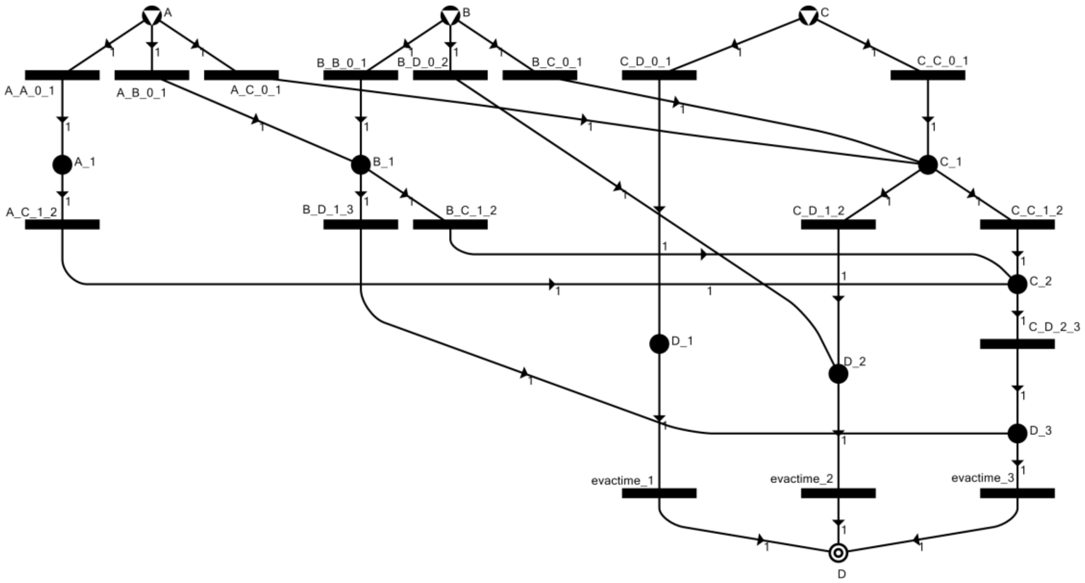

Figure 4: P-graph representation of the maximal structure for Figure 2 (Upper bound of the evacuation time T = 3)

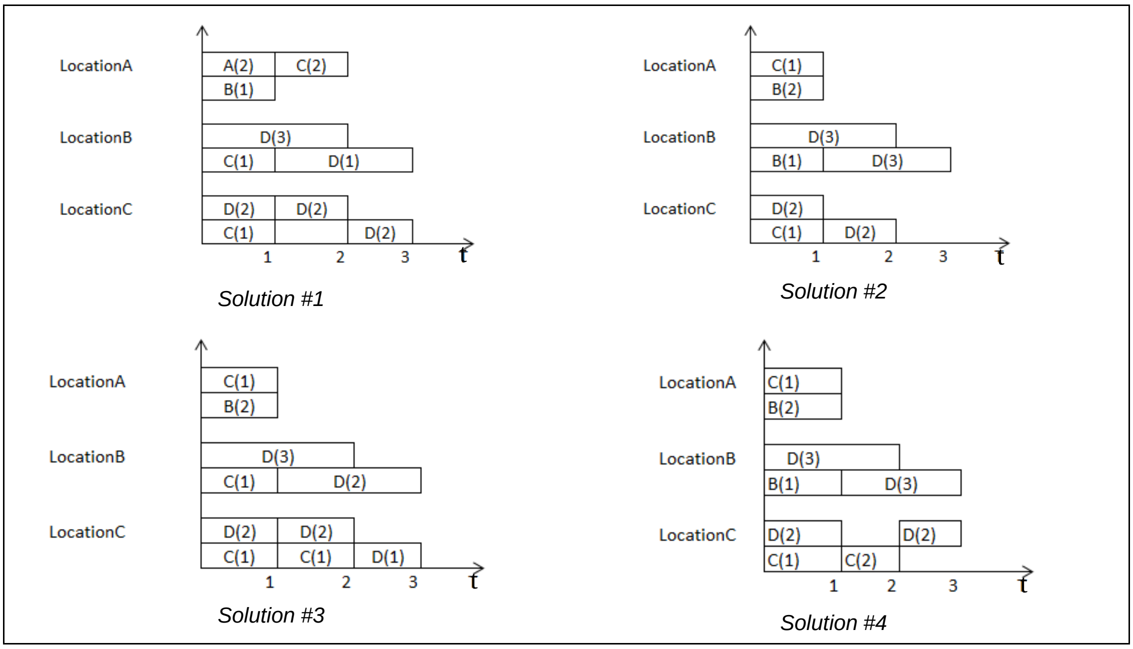

Figure 5: Four best evacuation route plans for the example. Y-axis represents departing locations, X-axis evacuation time, and rectangles route scheduling and the number of evacuees on each route

5. Conclusions

An algorithmic method has been proposed for generating the optimal building evacuation plan consisting of a set of evacuation routes and scheduling of evacuees on each route. The method has been devised by transforming the building floor map into P-graph representation and solving the resultant PNS_T problem by algorithms and software of the P-graph framework. The potential of the proposed method has been illustrated by applying it to an example.

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