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A NEW ILP MODEL FOR FINDING OPTIMAL EVACUATION PATHS IN EMERGENCY SCENARIOS

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We present a new time-indexed Integer Linear Programming model for the definition of optimal evacuation paths from an indoor area (museum, exhibition centre, etc.), in case of an emergency. The corresponding optimization algorithm has been integrated in a software tool that is powered with the data of the distribution of the visitors inside the considered site, provided by sensors or simulation tools. The output of the algorithm consists of a set of evacuation paths that will allow the visitors to reach the emergency exits in the shortest amount of time. In an *on-line* setting, such a tool provides the security department of the museum with safe evacuation plans that can be implemented in case of an emergency. Moreover, in a more *strategic* setting, it can be used as a simulation tool that can support the management to design the distribution of the exhibited works and to evaluate the maximum capacity of the rooms as well as the number and distribution of the emergency exits.

Keywords: *evacuation paths, integer linear programming, time-indexed formulations*

1. Introduction

The design, test, control and maintenance of safe and efficient evacuation plans for indoor spaces, both private or public, that are open to visitors, is a crucial issue for a municipal administration. Indeed, the problem regarding the definition of optimal evacuation paths has been widely studied in the literature, starting from the seminal work [1]. There, the author uses Integer Linear Programming (ILP) in order to model the problem as a maximum dynamic flow problem, where the capacity of each directed arc of the network depends on the amount of flow that uses the adjacent arcs (see [2] for a survey on the ILP-based approaches). More recently, in [3], an efficient algorithm has been proposed in order to calculate the evacuation paths from a building. The procedure minimizes the total evacuation time and assigns an optimal number of visitors to each of the defined paths. Unfortunately, the computational time rapidly grows with the dimension of the instance and the method cannot be used to get real-time solutions in real case scenarios. Other efficient approaches based on over-time flows or transshipment models can be found in [4, 5, 6]. Then, models and algorithms obtained by mixing optimization and simulation techniques have been defined in [7].

Here, we consider the problem of defining optimal paths for the evacuation of the visitors from a indoor area in case of an emergency (earthquake, fire, terroristic attack). In particular, we introduce a new time-index ILP formulation for the problem. The arcs of the directed graph that models the planimetry of the considered site are characterized by two given parameters assumed to be constant during the whole optimization process: the travel time and the max flow capacity in the time unit. This choice represented a good compromise among the accuracy of the results obtained and the computational time requested, that allows the whole procedure to be applicable in real case contexts.

2. The ILP model

2.1 Modeling the museum

Let R be the set of rooms/corridors (in the following, simply rooms) of the museum taken under consideration. Moreover, let $\underline{R} \subseteq R$ the set of rooms that are not available during the evacuation process. This can happen because of the emergency itself, or for different reasons (work in progress, maintenance, shortage of supervisory staff, etc.). For each room $r \in R$ we are given a capacity w_r, that is the maximum number of visitors that can simultaneously occupy the room at each instant of time. The planimetry of the museum is modelled by a directed graph $G = (N, A)$. The node set N is partitioned in the three subsets N_C, N_D and N_E. In particular: N_C are the *centroid* nodes, where the visitors are located at the beginning of the evacuation; N_D contains a couple of *passage* nodes for each door / gate among two rooms of the museum; N_E contains an *exit* node for each escape room of the museum. For each node $u \in N$, let $u(r) \in R$ be the room where the node belongs to and let $N(r)$ be set of nodes of each room $r \in R$. Clearly, $\cup_{r \in R} U(r) = N$. Then, for each arc $a = (u, v) \in A$, we are given: a travel time p_a and a capacity f_a, that is the maximum number of visitors that can traverse the arcs in a unit of time. Usually, the arcs of the graph G can be matched into symmetric couples (that is, for each $(u, v) \in A$, we also have $(v, u) \in A$. This rule admits two exceptions: i) one can enter in but not exit from an emergency exit; ii) one can exit from but not enter in an available rooms.

2.2 The ILP formulation

As we already mentioned, we introduce here a time-indexed ILP formulation for a new flow over time model of the problem. At the beginning of the evacuation process, we assume we are given the number v_u of visitors located in each centroid $u \in N_C$. Such a number can be provided by sensors located in the rooms, simulation models, estimations derived from historical data. Then, let T be the time horizon for the evacuation process. The variables of our formulation are the following

x_{ut} = number of visitors in node u at time t, $u \in N$, $t \in T$; y_{at} = number of visitors that start traversing arc a at time t, $a \in A$, $t \in T$;

$$q_{uv} = \begin{cases} 1 & \text{if arc } (u,v) \text{ is used by some visitor at during the evacuation process} \\ 0 & \text{otherwise} \end{cases} \qquad (u,v) \in A.$$

Moreover, in order to model the objective function, that is the minimization of the total evacuation time, we use the following binary variables

$$z_t = \begin{cases} 1 & \text{if all visitors reached the emergency exits at time } t \\ 0 & \text{otherwise} \end{cases} \qquad t \in T.$$

Then, we define a set of linear inequalities to model the following set of constraints:

- C1 *classical* flow conservation constraints that regulate the visitors located at each node of the graph at each instant of time;
- C2 at each instant of time, the room capacities cannot be exceeded;
- C3 at each instant of time t, the number of visitors that start traversing each arc $(u, v) \in A$ cannot exceed the flow capacity of the arc nor the number of visitors that are located in node u at time t;
- C4 at time t=1, the number of visitors in each node u is p_u;
- C5 if any arc (u, v) is used in the evacuation, then arc (v, u) is not.

3. The EVC-Suite

We used the ILP formulation defined in the previous section to solve the optimization problem of finding the evacuation paths that allows the visitors to reach the emergency exits of the museum in the smallest possible amount of time. In particular, we implemented a Python code that writes the ILP formulation which is then solved by the python callable libraries of the open source ILP optimization package COIN-OR. The whole optimization procedure is then embedded in a software package, called EVC-Suite and implemented by JustAnother s.r.l. EVC-Suite implements friendly routines that allows the user to easily: i) construct the model of the museum; ii) set the distribution of the visitors in the museum at the moment of the emergency; iii) solve the current optimal evacuation paths problem; iv) display the solution in a easily interpretable way. In Figure 3 a detail of the web app is depicted.

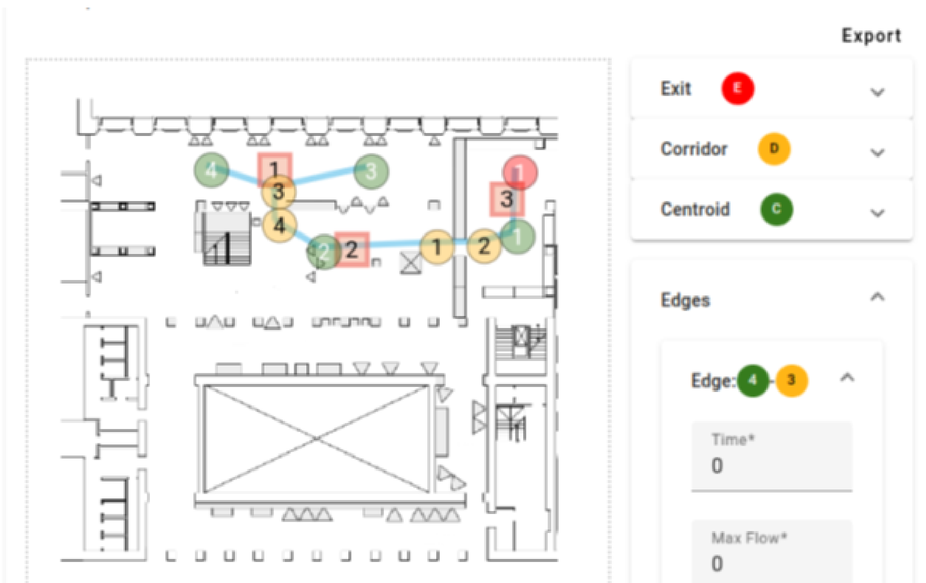

Figure 1: Screenshot of the ECV-Suite web app with details of the graph modeling the museum planimetry.

The overall approach has been tested on several instances that have been derived from the exhibition sites of the Museo Delle Civiltà in Rome (see here, the on-site experimentation conducted by CNR and NexSoft s.r.l. within the Smartour project [8]) and the S. Rocco Hub in Matera. All the computation experiments carried out gave evidence of the validity of the proposed approach, both in terms of quality of the solutions provided as well as of the computational times required.

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