FDS+Evac: Modelling Social Interactions in Fire Evacuation

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ABSTRACT

In recent years computational simulation of fire evacuation has become an interest of many scientists and several different simulation models have been developed. Nevertheless, many of these models do not take into account the social interactions between people, which greatly affect their behaviour. The effect of the fire and smoke on people's behaviour has also been rarely discussed. However, these factors are very important to the final outcome of an evacuation, and thus, have to be taken into account in a comprehensive evacuation simulation model. This paper presents computational methods for modelling the behavioural effects of evacuations. The developed models either are or will be implemented in an evacuation simulation program called FDS+Evac, which is a part of the fire simulation tool Fire Dynamics Simulator (FDS). Like the current version of FDS, also the evacuation module, FDS+Evac, is publicly available.

INTRODUCTION

The most important objective of a fire safety design is to ensure that people can safely escape from a building in the case of fire. The fire classes and numerical criteria based fire regulations may be adequate for normal buildings, but may not take into account the special issues of large and complicated buildings, like shopping centres, assembly facilities, *etc*. Performance based fire codes allow the use of numerical simulation of fire and evacuation processes to be used to improve fire safety in such buildings. However, the usability of many current evacuation models is limited, because they do not take into account the individual properties and decision-making processes of people, the dynamics of large crowds and the interaction between fire and people.

Many evacuation models assume also that at the start of the evacuation each person heads straight to the nearest exit. According to social psychological literature, this assumption is far from the truth. According to Pan,[1] people who have come to building together, *e.g.* family members, also tend to leave together. Thus, if these people are not right next to each other, they will try to get together before exiting the building. People also tend to prefer the familiar exit routes even if there were faster ways to exit available. According to Proulx,[2] evacuees prefer familiar alternatives because they feel that unknown alternatives increase the threat. In many cases people also ignore some exits because they are unaware of their existence.

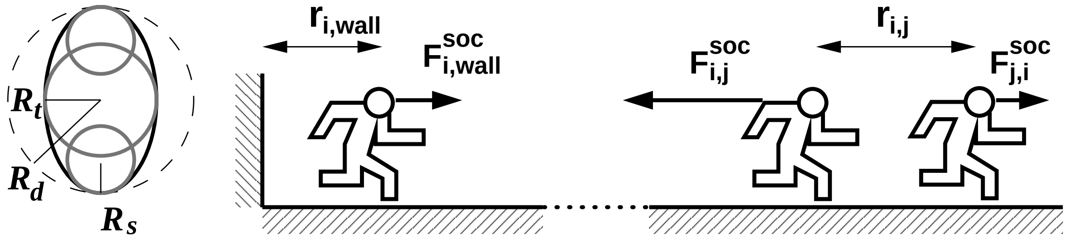

FIGURE 1: Definitions of the human dimensions and the concept of the "social force".

In this paper, a recently developed evacuation programme FDS+Evac[3, 4, 5] is presented. The movement algorithm of the programme allows modelling of congested situations, including 'panic' situations, and allows interaction between evacuation simulation and the state-of-the-art fire simulation. A person is treated as autonomous agent, *i.e.*, each person makes his/her own decisions on exit routes, and this decision making process is affected by fire-related conditions.

The various validation and verification cases of FDS+Evac are reported on a VTT publication.[6] During the development work of FDS+Evac, experiments on human egress were performed to provide validation data. These experiments are reported in a separate publication.[7] FDS+Evac is implemented as a part of the fire simulation tool Fire Dynamics Simulator (FDS).[8, 9] FDS is a computational fluid dynamics software using large eddy simulation to model turbulence and is especially designed to simulate fire induced flows. The companion programme of FDS is Smokeview,[10] which is used to visualise the results of FDS fire simulations. This fire simulation environment is publicly available at a web page.[11]

In this work, a new model is developed for the group behaviour and the existing game-theory-based model for exit selection is improved by introducing a more accurate technique for the queuing time estimation. The presented models have not yet been implemented in the publicly available version of FDS+Evac (FDS version 5.0.0, Evac version 1.10), which is available at the web page *http://www.vtt.fi/fdsevac/*.

MODEL DESCRIPTION

Human Movement Model

The starting point of the human movement algorithm of FDS+Evac is the method introduced by Helbing's group.[12, 13, 14, 15] This movement model is generalised to a more realistic representation of the human body with three circles along the lines given in the paper by Langston *et al.*[16] The basic idea of the model of Helbing's group is the so called "social force", which is a repulsive interaction force that describes the psychological tendency of two pedestrians, say i and j, to stay away from each other (or away from walls), see Fig. 1. The simplest form for this force is an exponential decay, but in FDS+Evac the anisotropic formula proposed by Helbing *et al.*[14] is used.

FDS+Evac uses the laws of mechanics to follow the trajectories of the humans during the calculation. The elliptical body shape of the human body is modelled as three circles, see Fig. 1. These models of humans are moving on two dimensional planes, which are modelling the geometry of the building. Inclines, like stairs, are projected into these two dimensional planes.

TABLE 1: Unimpeded walking velocities and body dimensions in FDS+Evac. The offset of shoulder circles is given by $d_s = R_d - R_s$, for the definition of the other body size variables, R_d, R_t, and R_s, see Fig. 1.

Body type	R_d (m)	R_t/R_d (-)	R_s/R_d (-)	d_s/R_d (-)	Speed (m/s)
Adult	0.255±0.035	0.5882	0.3725	0.6275	1.25± 0.30
Female	0.240±0.020	0.5833	0.3750	0.6250	1.15± 0.20
Male	0.270±0.020	0.5926	0.3704	0.6296	1.35± 0.20
Child	0.210±0.015	0.5714	0.3333	0.6667	0.90± 0.30
Elderly	0.250±0.020	0.6000	0.3600	0.6400	0.80± 0.30

The different floors and separate parts of the building are connected using nodes that moves persons from one plane to the next plane.

Each person follows his/her own equation of motion on a horizontal plane describing a floor of a building:

$$m_i \frac{d^2 \mathbf{x}_i(t)}{dt^2} = \mathbf{f}_i(t) + \boldsymbol{\xi}_i(t) \ , \qquad [1]$$

where $\mathbf{x}_i(t)$ is the position of the person i at time t, $\mathbf{f}_i$ is the force exerted on the person, m_i is the mass, and the last term, $\boldsymbol{\xi}_i$, is a small random fluctuation force. The velocity of the person, $\mathbf{v}_i$, is given by $d\mathbf{x}_i/dt$. The rotational degrees of freedom are treated similarly than the translational ones, *i.e.*, each person has his/her own rotational equation of motion on a 2D plane:

$$I_i^z \frac{d^2 \varphi_i(t)}{dt^2} = M_i^z(t) + \eta_i^z(t) \ , \qquad [2]$$

where $\varphi_i(t)$ is the body angle of the person i at time t, I_i^z is the moment of inertia, η_i^z is a small random fluctuation torque, and M_i^z is the total torque exerted on the person by its surroundings.

The forces acting on humans are both the physical contact forces and the psychological, so called "social forces". The force $\mathbf{f}_i$ contains also a "motive force", which (de)accelerates a person towards his/her target walking speed. The total torque contains similar "motive torque", which turns a person to head towards the walking direction. The default body sizes and walking speeds of the predefined human types in FDS+Evac are listed in Table 1. For the full description of the movement equations and the values of the parameters used in the equations, see the papers by Korhonen *et al.* [4, 5]

The translational and rotational equations of motion are solved using a modified velocity-Verlet algorithm, where the translational motive force part is solved using a self-consistent dissipative velocity-Verlet algorithm [17] and the other parts are solved using the standard velocity-Verlet algorithm, which can be found in any basic textbooks on molecular dynamics simulations. The time step used in the algorithm is adjusted during the simulations by the maximum forces exerted on humans. The minimum time step varies between 0.01 and 0.001 seconds, by default.

Smoke reduces the walking speeds of humans due to the reduced visibility, its irritating and asphyxiant effects. Recently, Frantzich and Nilsson [18] made experiments on the effect of

TABLE 2: Preference order of exits used in the model. The combinations of the last two rows have no preference. This is because the evacuees are unaware of the exits that are unfamiliar and invisible, and thus, can not select these exits.

preference	visible	familiar	disturbing conditions
1	yes	yes	no
2	no	yes	no
3	yes	no	no
4	yes	yes	yes
5	no	yes	yes
6	yes	no	yes
No preference	no	no	no
No preference	no	no	yes

smoke concentration on the walking speeds of humans. They used larger smoke concentrations than Jin[19] and they fitted an analytical formula to the experimental values, which is used in FDS+Evac. The toxic effects of gaseous fire products are treated by using Purser's Fractional Effective Dose (FED) concept.[20] The present version of FDS+Evac uses only the concentrations of the narcotic gases CO, CO_2, and O_2 to calculate the FED value and the effect of CO_2 is only due to the hyperventilation, *i.e.*, it is assumed that the CO_2 concentration is such low that it does not have narcotic effects. An incapacitated person is modelled as a person, who does not experience any social forces from the other persons and whose target walking speed is set to zero.

Exit Selection

Game theoretic reaction functions and best response dynamics are applied to model the exit route selection of evacuees. In the model each evacuee observes the locations and actions of the other evacuees and selects the exit through which the evacuation is estimated to be the fastest. Thus, the exit selection is modelled as an optimisation problem, where the evacuee tries to select the exit that minimises the evacuation time.[21]

The estimated evacuation time consists of the estimated time of walking and the estimated time of queueing. The walking time is estimated by dividing the distance to the exit by walking speed. The estimated time of queueing is a function of the actions and locations of other evacuees.

It is also assumed that people change the course of action only if there is an alternative that is clearly better than the current choice. This behaviour is taken into account by subtracting a parameter from the estimated evacuation time through the exit currently chosen. This is an individual parameter that can have different values for different pedestrians. Hence, it is possible to consider the differences in the patience of the evacuees.

Apart from the locations of exits and actions of other people, there are also other factors that influence the evacuees' decision making. These factors are the conditions related to the fire, the evacuees' familiarity with the exits and the visibility of the exits. The effect of these factors is taken into account by adding constraints to the evacuation time minimisation problem.

According to the three factors mentioned, one can divide all exits to seven groups, each of the exits belonging to one group. The groups are given an order of preference. In the model, the preference order of exit groups shown in Table 2 is assumed for each evacuee.

This exit selection algorithm consists of the above described two phases. First the exits are divided to the preference groups according to Table 2. Then, an exit is selected from the most preferred nonempty preference group by minimising the estimated evacuation time.

The exit selection model has been implemented to the FDS+Evac software. However, the current, publicly available version does not include all of the features presented. Currently the estimated evacuation time is calculated only according to the distance to the exit and the possible queue formed by other people is not taken into account. When calculating the distances to exits, the current version uses a straight line from the agent to the exit and does not consider the possible walls that may block this straight route.

Groups

An evacuating crowd consists of individuals that interact with each other. These interactions may affect the evacuation largely and should be taken into account in simulation models. The interactions are strongest between people that have come to the gathering together, as they also tend to leave together.[1] These interactions between familiar people are called as “group effect” in this work. The actions of a group are divided into the following two stages:

1. *The gathering stage*. The group members walk towards each other to gather the group.
2. *The egress stage*. The group moves together along the chosen exit route.

The group model has also been tested in the FDS+Evac software, but it is not publicly available in the current version FDS+Evac. The group behaviour is achieved by altering the direction of the motive force of Helbing’s model. In the gathering stage the motive force of each person belonging to a group points to the centre of the group. This makes the group gather together. In the egress stage the direction of the motive force $\mathbf{e}_i^0(t)$ is calculated by

$$\mathbf{e}_i^0(t) = \alpha\,\mathbf{e}_{C,i}^0(t) + (1-\alpha)\mathbf{e}_{F,i}^0(t), \tag{3}$$

where $\mathbf{e}_{C,i}^0(t)$ is a unit vector pointing to the centre of the group and $\mathbf{e}_{F,i}^0(t)$ is a unit vector pointing to the direction where the person would go if he/she would behave as an individual, *i.e.*, towards the exit route direction. The parameter $\alpha \in [0,1]$ is called as group effect parameter. The larger the group effect parameter is, the more eagerly the group members try to keep the group together during egress.

RESULTS AND DISCUSSION

The effect of the group effect parameter α was studied with test simulations. The test geometry was a wide and open corridor through which the evacuees were set to walk. The results of the test simulations are shown in Fig. 2. It can be seen that when the value of α is less than 0.28, the average speeds of groups is just a little slower than the speeds of independent evacuees. But when α is increased to 0.29 or above, the average walking speed rapidly decreases. By observing the test simulations it can be noticed that as the value of the group effect parameter

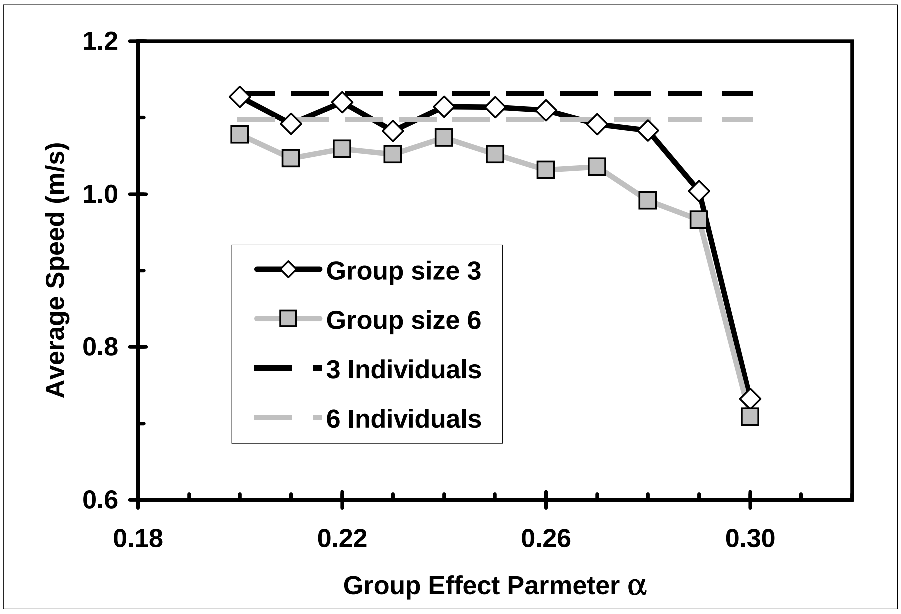

FIGURE 2: The average walking speeds in a wide corridor for groups of 3 and 6 persons and for 3 and 6 autonomous agents.

increases above 0.28, the directions of the motive forces become unrealistic. As a conclusion one can set an upper limit of 0.28 for the proper value of the parameter.

Public Library

The evacuation of the main library of Helsinki University of Technology (HUT) was carried out as part of the safety training program of the library staff. HUT is located in the city of Espoo in Southern Finland and the evacuation took place in early spring 2006, when snow still covered the landscape. The staff was informed that the evacuation would take place in the given day. The library visitors were notified on the evacuation exercise by printed notes on the entrance doors. Exact time was not specified, nor were the details of the evacuation. The floor plan is shown in Fig. 3. Shown are only the part of the second floor, which is open to public. The main exit staircases lead to a main entrance lobby at the first floor. VTT was able to participate this evacuation exercise as an observer. Immediately before the evacuation, VTT researchers entered the building to make observations on crowd behaviour and outside the building to observe all doors. Also different technical observation methods, like video recorders, RFID technology, and a stereo camera, were used to monitor some of the doors, but unluckily there were no technical observation method implemented on the emergency exit door, which the most of the building occupants used. Thus, the technical observation methods are not presented in this paper. An interested reader is suggested to read the VTT publication on the experimental part of the development work of FDS+Evac.[7]

A smoke generator was put in operation in the lobby, thus preventing the use of the main staircases. A fire alarm went off 37 seconds after the smoke generator was started, and evacuation began. The alarm signal was a loud bell sound. In 5 minutes 52 seconds after the fire alarm, all 189 people that had been in the building had evacuated.

A great majority of people decided to evacuate through the north door, which was in the opposite end of the building to the ’fire’. The staff members tried to give instructions and distribute

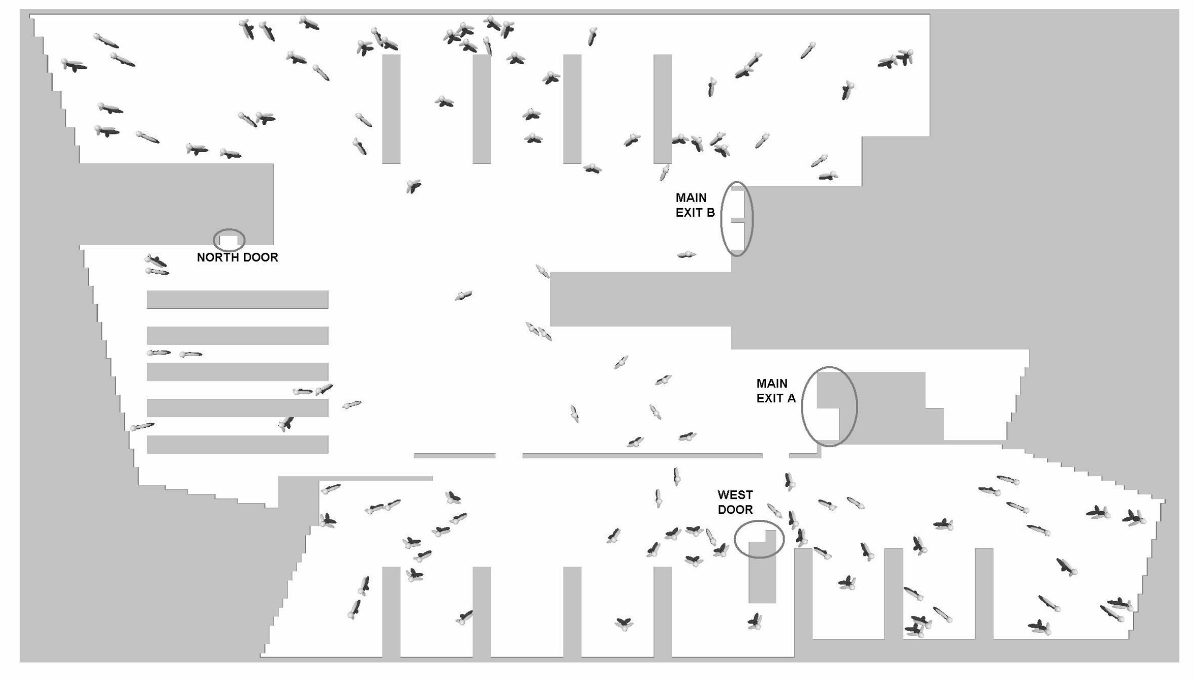

FIGURE 3: A snapshot from a FDS+Evac simulation shows the geometry of the model for the second floor of the public library (the dimension of the model is 64×36 m^2). Shown are also the random initial positions of the visitors in one of the many FDS+Evac simulations.

people evenly to the two available stairways, the north and west doors, but many evacuees did not pay much attention to these instructions. The north door was the only door with observed crowding. The north door leads to an exit path that was modelled as a 1.0 m wide door leading to a 1.2 m wide staircase leading down to a 0.75 m wide emergency exit door on the first floor (the ground level). The north door and the staircase are known to almost all visitors of the library, because this route is routinely used to access the collections on the first floor of the library, but it might not be commonly known that there also exits an emergency door which leads directly to outside.

The evacuation trial of the HUT main library was modelled using FDS+Evac. The simulation geometry and the initial positions of the persons are shown in Fig. 3. As the majority of persons in the building used the north exit door, the main results are for this door. The persons were allocated for the north and west doors according to the ratio observed in the experiment by setting the preference of the north door as a “known door” for about 60 % of the evacuees, see Table 2 for the preference order of the doors used in the exit selection algorithm of FDS+Evac. The smoke on the main entrance lobby was modelled by blocking the main exit stairs after 30 s from the start of the simulation, which refers to the time when the alarm went off in the evacuation trial.

The simulations were performed using the default values of FDS+Evac for the human properties except for the anisotropy parameter of the social force a value of 0.3 was used. The stairs were modelled as an incline, whose height was 4.0 m and length of the base was 5.0 m. FDS+Evac models the movement of humans in stairs by reducing their walking speed along the stairs (or incline). The walking speed of persons along the incline of the stairs is obtained by multiplying the horizontal walking speed by a reduction factor. Going up the stairs is modelled similarly, but

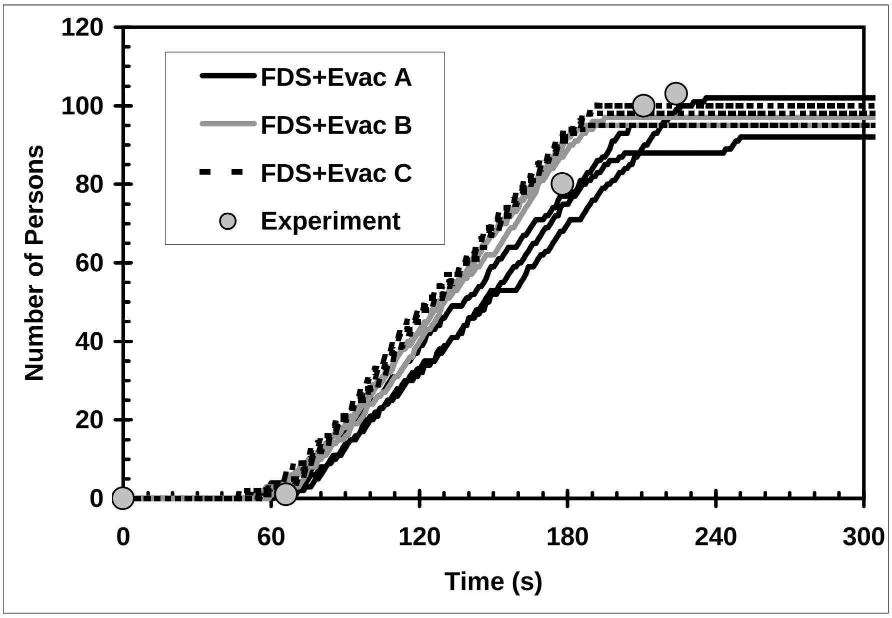

FIGURE 4: The calculated and experimental results for the north emergency exit door. The FDS+Evac cases A, B, and C correspond to calculations, where walking speed reduction factors for the stairs were 0.55, 0.65, and 0.75, respectively.

a different speed reduction factor is used. Previous experience has shown that a speed reduction factors of the order 0.6–0.8 give nice human flows in stairs. [6]

The premovement times were generated from a symmetric triangular distribution with mean of 31 s and lower and upper limits of 11 s and 71 s, respectively. This is a crude estimate based on the video recordings taken inside the building during the evacuation trial. For the north door, the simulations are relevant even though the premovement time is somewhat arbitrary, because the flow rate is mainly determined by the geometry and the crowd dynamics during the queueing process.

The cumulative number of evacuated people for the north door is shown in Fig. 4. The flow of people out of the north door was quite steady from about 70 s to 200 s from the alarm, and probably controlled by the width of the stairway and the doors leading to the staircase and outside. The flow rate was found to be about 0.7 persons per second. However, the flow rate is based on the manual bookkeeping, and the uncertainty of the actual flow rate is quite high. Also the simulation results of various FDS+Evac runs are shown in Fig. 4. The FDS+Evac cases A, B, and C corresponds to simulations, where speed reduction factors for stairs were 0.55, 0.65, and 0.75, respectively. Each case was run three times, because FDS+Evac uses random initial properties and positions for the modelled persons. It is seen that when the speed reduction factor has a value 0.55 the stairs start to control the flow rate. For a faster movement in stairs the exit door at the bottom of the stairs controls the flow rate. This is probably the case seen in the actual evacuation experiment, and thus, the speed reduction factor about 0.7 might be a good choice to be used in the simulation of the stairs. The emergency exit door opened to a small landing outside of the building where only a very narrow path tampered in snow left away and evacuating persons were walking along this path as one row making the exit effectively one person wide.

CONCLUSIONS

This paper presents a recently developed evacuation modelling programme FDS+Evac that allows the simulation of fire and evacuation at the same time. FDS+Evac can be applied to buildings where the floors are mainly horizontal. FDS+Evac is made public on the web page *http://www.vtt.fi/fdsevac/* and its executable and source code are included in the FDS (version 5) distribution.[11] In this paper, FDS+Evac is applied to simulate an evacuation trial in a public library. FDS+Evac was found to run satisfactorily for this case.

This paper also presents the social interaction models and decision making algorithms which are planned to be included in the FDS+Evac. The presented models relate to exit route selection and evacuees' tendency to act in groups. Parts of these models are already implemented in a test version of FDS+Evac. This paper presents the results of a test related to the proper value of a parameter in the group model. Boundaries for a realistic value of the parameter were found.

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