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Exit selection process during crowd evacuation, modelled on the cockroach emergent behaviour

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Abstract. Groups of living creatures are often faced with searching for resources and choosing between one or more alternatives of resource site. Such a process is connected either with calm food acquirement or looking for a safe place to hide from danger. The question is, what kind of criteria are taken into consideration and what induces the collective decision, when all individuals in a swarm are equal. This paper identifies a simple mechanism of shelter selection by cockroach herd, whereby an emergent decision is made with limited information and without centralization of information processing or comparison of available solutions. The mechanism leads to the optimal benefit for both a group and an individual. The proposed model activates swarm self-organization and is independent of species, therefore, a possible application to human crowd control has been studied.

Key words: swarm, crowd, cockroach, ethology, behaviour.

1. Introduction

Cockroaches (*Blattaria, Blattodea*) are the order of insects of more than 3500 species, among which 16 occur in Poland, and most popular are there oriental cockroach (*Blatta orientalis*) and german cockroach (*Blatella germanica*) (Fig. 1).

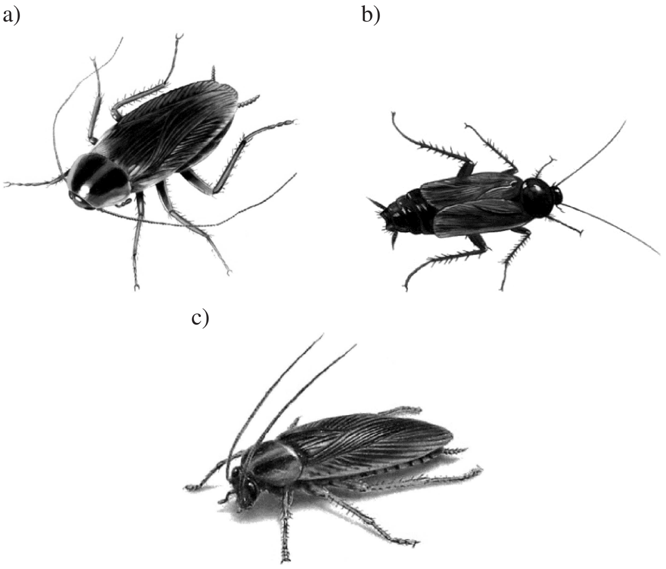

Fig. 1. American cockroach (*Periplaneta americana*) (a), oriental cockroach (*Blatta orientalis*) (b) and german cockroach (*Blatella germanica*) (c)

The ancestors of modern forms of those insects evolved about 354-295 million years ago and gave a rise of, inter alia, the line of termites. Cockroaches at most occur in tropical, oriental countries, and many species exhibit synantropic behaviour, what means that they are capable of using habitat, which was intensely transformed by the human, for living with benefits.

What is more, they are high invasive species, so they are able to disperse quickly and freely, without any control. When it comes to their body look (Fig. 1), prominent, covered with bristle and made of many parts antennae stand out, and their main function is to inspect and analyse local surroundings. Also characteristic are lissom limbs, which are helpful in fast running and efficient movement on the challenging surface [1, 2]. Cockroaches are omnivorous and lead a cryptic, hidden life. They stay active mostly in the night. Even though they adapt very quickly to various environments, but yet they prefer to gather in moist and warm places [3].

An expansion attribute of cockroaches has a social form and a lot of their collective behaviours indicate some herd features. A chemical, odorous substance, which is emitted with their feces, named pheromone, is used by them to mark the territory. A part of pheromone is also discharged to the air and in volatile form makes a collective contact factor, thanks to which cockroaches are able to identify one another and take group actions and decisions [4]. Typical example of such behaviour is looking for food. Isolated units are following the signal of pheromone in directions, from which they smell greatest concentration, and that is why they are able to reach their fellows next to the source of food or water. A main role in the process of recognizing and interpreting signals from the environment plays highly developed oral apparatus. During dangerous situations a pheromone signal is immediately read and leads solitary animals to a place, where other ones have been hiding. On the ground of reactions of cockroaches, which are based on analysis of odorous signals, one is able to observe emergent behaviour, what means that it is behaviour, in which individual attitudes of a group of units transform afterwards into one, coherent behaviour of whole herd [5].

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2. Emergent cockroach behaviour

Cockroaches are extraordinarily skittish animals, what explains being active especially in the night. It turns out, that facing the risk or danger not only they react in a pretty impulsive way, but also their behaviour has a deep sense for the whole herd. Cockroaches do not possess a hierarchical social organization, which would allow them to set a leader or leaders, even for a while. However, thanks to proper individual interactions in the herd, they are able to solve complex decision issues.

There was an experiment carried out, in which group of 50 cockroaches was set in the area with three shelters inside. In each shelter only 40 cockroaches could hide at one time. It turned out during the experiment, that cockroaches, facing some symptoms of danger, are capable of quick dispersing the herd, they explore the area, find shelters and then find an optimal solution of multi-criteria optimization, where criteria are the fight for resources and cooperation with one another. The whole process seems to be like gathering information, exchanging it inside the herd, consulting and finally making one, common decision. Those pieces of information are gathered and exchanged not only through pheromone emission, but also through the touch and vision, and very important role play here sensitive antennae [5]. As a result, instead of overcrowded one shelter, there occur two used shelters, with about 25 individuals in each of them (Fig. 2). The third one remained empty. Probably that was, because cockroaches had decided to split into as few groups as possible, providing that all of them could hide in an available shelter. Dividing into three groups was also possible, but obviously animals decided, that under such conditions maximum granulation and disperse of the herd is not optimal from the viewpoint of security. Therefore, cockroaches optimize the size of their group, depending on situation, in which they stay, and when there is a requirement, they divide the herd. Thus, when shelters had been changed into bigger ones, with the capacity of more than 50 cockroaches, and an experiment had been repeated, whole crowd hid in the one shelter [5].

a) b)

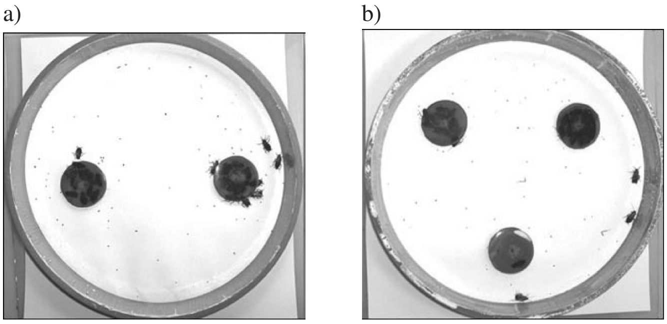

Fig. 2. Cockroach experiment with two (a) and three (b) shelters

Because of their night activity, one of factors, which cockroaches find dangerous is the light. Almost all species of cockroaches exposed to light, immediately run away, dispersing the herd and looking for a shelter. Other experiment's results showed, what is the mechanism of decision making about the escape and its direction.

There are two decision criteria, which have an impact on individual's behaviour. First one is connected with a decision, whether to escape or not, and it is the concentration of dangerous factors. When it comes to the described experiment, that criterion was local intensity of the light. In turn the second one is the density of other individuals and its distribution. In carried out experiment small robots, imitating real cockroaches (Fig. 3), were very helpful in proving that cockroach decision is dependent only on two criteria. Those robots were covered with pheromone in advance, to make them be accepted by real animals as individuals of their own species [6, 7]. It turned out, that those robots may be a tool to control real cockroaches and make whole herd go, where under natural conditions it wouldn't go.

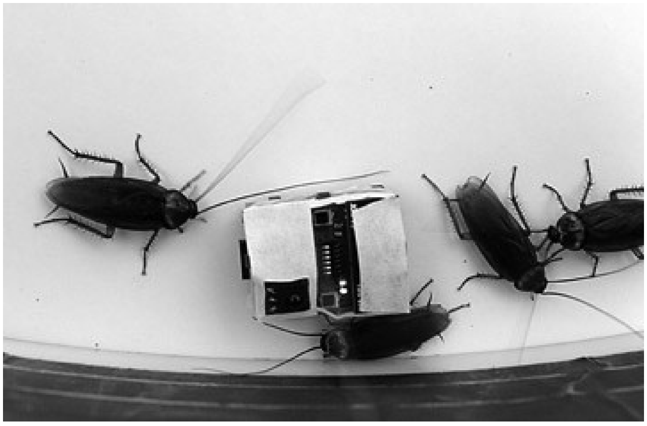

Fig. 3. Robotic cockroach interacts with real cockroaches during experiment

During the first part of the experiment robots were not used. Nevertheless that first part confirmed results of previous experiment [5], because when a herd had been exposed to light, all members of it ran quickly to one, big shelter. At the beginning all cockroaches had been running randomly and bumping into one of two prepared shelters. However, when density of individuals in one of shelters had reached the critical mass (and so did pheromone concentration), all individuals which were out of that shelter, were strongly attracted to it. In a timely fashion all cockroaches gathered in one shelter [6, 7].

In the second part of the experiment robot cockroaches played their part. At first they were tested as new members of population and it turned out, that behaviour of the herd is not disturbed. Then, one of shelters was moved to the place, where intensity of the light was significantly higher, and to which place cockroaches normally wouldn't go. Robots were programmed to choose just that shelter and it turned out, that after reaching the critical mass by robots and some cockroaches, all other living individuals joined the shelter [6, 7]. Then conclusion is that unified behaviour of a percentage of herd is able to make the rest do the same thing.

Another experiment proved, that cockroaches, just like dogs or humans, are predisposed to classical Pavlov experiment. Cockroaches stimulated by smells different from their own pheromone and simultaneously given a sugar, which they adore, learned the connection between those two factors, and when another smell emission comes, they were strongly drooling, what means that they were expecting food [8]. It is surprising, that such primitive nervous system, which cockroaches possess, is able to learn quickly and remember the schema. This fact is the confirmation for high adaptive skills and ability to obtain new behavioural features, which are then passed on by the natural selection. Similar results of experiments with Pavlov test were observed among bees and fruit flies [8], probably because of their exceptional sensitivity to smells.

Cockroaches demonstrate the ability to personal behaviour, what is desired not only by the individual, but also is set beside advantages for the herd. Anxious changes in the area, where they stay, like lack of food, hazards or predator, are quickly identified by sensitive antennae and cause early reaction of the animal, which has to choose the direction of escape and then takes into consideration both, scale of changes and pheromone signal, what reflects distribution of other individuals. With regards to searching for food it is not the most important issue, because changes of the environment aren't so rapid in this case and effects aren't quickly perceptible. But when it comes to hazardous situations, with danger factors, such behaviour is very important, because it states the key element of either individual or herd survival [9, 10].

3. Exit selection algorithm

An exit selection algorithm for human crowd is inspired by social behaviour of cockroaches and their individual actions, which involve an emergent herd decision. It takes into consideration limited information of the environment observed by individuals and shows, how an emergent load balancing can be achieved by self-organization.

There is a human cluster of $i = 1, \ldots, N$ individuals u_i, with average size (diameter) of s, which are able to observe and recognize details of their surroundings within sight radius of r and which move with an average velocity of v, located in an area with $j = 1, \ldots, M$ exits e_j, each one of size w_j. Each one of individuals is situated within r_{ij} distance from exits.

Function approximation for a bandwidth of the exit (what should be considered as a maximum number of individuals, which are able to make use of an exit during a period of time) is defined as follows [11]:

$$b_j(w_j, s, v) = \left| \left(\frac{2\sqrt{3}}{3} \frac{w_j - s}{s} + 1 \right) \frac{v}{s} \right| \qquad w_j \geq s. \quad (1)$$

Quantity of individuals, which are waiting in the queue of particular exit can be calculated according to Eq. (2):

$$cm_j = \sum_{i=1}^{N} u_i : \underset{k=1,\ldots,M}{\forall} (r_{ij} \leq r_{ik}) \wedge r_{ij} \leq r. \quad (2)$$

In turn, for a particular individual, situated within r_{ij} distance from particular exit, important is quantity of individuals cm_{ij}, situated closer to that exit than him:

$$cm_j = \sum_{i=1}^{N} u_i : \underset{k=1,\ldots,M}{\forall} (r_{ij} \leq r_{ik} \wedge r_{ij} < r_{ij}) \wedge r_{ij} \leq r. \quad (3)$$

Then, the expected time of using an exit by a particular individual can be calculated as a sum of time needed to approach the exit through the open space and possible additional queue waiting time (at the end of the whole process of using the exit) as in the Eq. (4):

$$t_{ij} = \frac{r_{ij}}{v} + \frac{cm_{ij}}{b_j}. \quad (4)$$

For a more detailed description and technical specification of queuing process, one should make use of queuing systems literature [12].

If maximum expected queue time for impatient individuals is $t_{\max}$ and an attractive threshold value of a critical mass (size of group of individuals, which can be seen by an individual from the distance longer than r and which is able to attract attention of a single individual) is assumed as $cm_{\min}$, then an algorithm of exit selection for each individual can be described:

1. Move towards randomly chosen direction,
2. For all exits calculate cm_j. For all exits, that are situated within sight, calculate t_{ij}.
3. Make a set of analysed exits, which contains:
   – Exits, that are situated within sight, for which $t_{ij} \leq t_{\max}$;
   – Exits, for which $cm_j \geq cm_{\min}$.
   4.1. If created set equals $\emptyset$, then $\rightarrow$ 1.
   4.2. Else from the set of exits select one with the smallest value of t_{ij}.
5. Go to selected exit $\rightarrow$ 2.

4. Experiments

For experiment needs a model of a special room with dimensions of 20×20 meters was prepared. In walls of that room four exits with standard dimension of 80 centimetres were located and emplaced as in Fig. 4. A crowd with quantity of 250 individuals was evenly distributed indoor, visibly close to one of exits (e_1). Each one of individuals had size of 50 centimetres and was able to move with velocity of 1.4 m/s. Perception of individuals was fixed at a level, which guaranteed that individuals were unaware of the existence of all the exits. Sight radius amounted 6 meters.

First part of experiments was focused on roles and relevance of algorithm parameters, which are maximum queuing time $t_{\max}$ and critical mass $cm_{\min}$.

Maximum queuing time represents the patience of individuals. It shows, how long they are able to wait in a queue for service, what is in this case the use of an exit. The parameter $t_{\max}$ is strongly connected with t_{ij}, which contains the sum of two parts of service. The first one is the time of reaching by an individual the exit area, after it was picked out. An exit area is a round area located directly in front of the exit. There may be a queue to the exit on that area, some individuals, which don't state a queue or it may be empty. Second part of t_{ij} is obviously $t_{\max}$. Therefore t_{ij}, used in the algorithm, states, how much time an individual has to commit to use an exit in relation to his position against all the exits. Maximum queuing time $t_{\max}$ is the key part of t_{ij}, because if there was no queue and no $t_{\max}$, decision of which exit individual should choose would depend only on distances from all the exits. Such situation is not much interesting and unprecedented when there are not just single individuals, but a crowd.

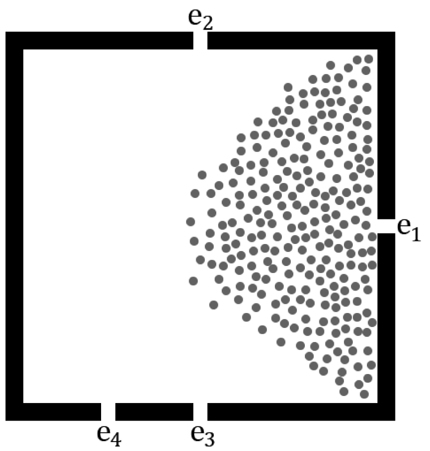

Fig. 4. Simulation area with marked crowd and exits

Figure 5 shows, what is the dependency between time of evacuation of test room and $t_{\max}$. To make results completely independent of the scale of critical mass, it was disabled ($cm_{\min} = 1$). For high values of $t_{\max}$ (more than 60s), which are enough for each individual to stay and wait for service in any exit, individuals just stay in a queue of first recognized exit. How can be expected, values of $t_{\max}$ higher than 60s don't change anything in evacuation time. Around that value there is a local optimum, because a few individuals from the edge of main queue (exit e_1) try to find an exit with better t_{ij}, because for exit e_1 they get $t_{ij} > t_{\max}$. Such behaviour not for all of them is profitable (there are going to be new queues in other exits, which those individuals don't expect and don't take into consideration in their assessments, when they move away from exit e_1) and that's why the evacuation time is a little higher on that point.

With lower values of evacuation time is going better till about 32s. The improvement is clear and essential. The explanation of such effect is that values of $t_{\max}$ from that range (32s – 60s) are not enough for significant number of individuals to stay in queue of exit e_1. They start searching for exits, which t_{ij} fulfil assumed $t_{\max}$. When more exits are found one can observe, that there occurs an emergent effect of exits load balancing. Alternate exits make evacuation time shorter. Therefore a little impatience among individuals in crowd impacts significantly and positively on evacuation time in an area with more than one exit.

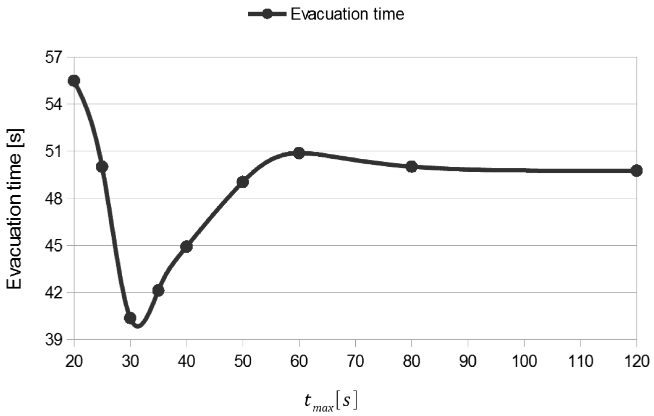

Fig. 5. Dependence of evacuation time on maximum queuing time

As one can see in Fig. 5, equally significant impact on evacuation efficiency, but this time negative, has impatience, which is too extreme. When individuals are so impatient, that they are unable to wait in queue for more than 30 seconds, none of available exits fulfil for them $t_{\max}$. They start to float around and can't decide to choose an exit or they choose an exit, but a while later, when queue enlarges (more individuals decide to pick that queue), they resign and keep trying to find a better exit. Such behaviour reflects afraid, nervous state of individuals. They are unable to stay calm for longer period of time. This may be a preliminary phase of crowd panic in some situations. The indecision of many individuals (not all of them, because those, which are close enough to an exit, in small queues, keep staying there) makes a lot of fuss and chaotic moves among the crowd. Individuals have to pass one another, movement is going to be not effective and as a result of all of that factors, time of the evacuation quickly grows.

To sum up, $t_{\max}$ (patience of individuals) is relevant parameter, which has strong impact on time of evacuation. When individuals are moderately impatient, the improvement of evacuation efficiency may be up to 20%, but when they start to behave not so rationally and become afraid or nervous, the change can be similarly significant but in negative way.

Next question is, what is the role of critical mass ($cm_{\min}$) and its impact on evacuation. Critical mass represents a vulnerability of individuals and their reaction on actions taken by other individuals or coherent groups of individuals. Since rationally thinking individual is able to observe the neighbourhood and interpret its characteristic.

Figure 6 presents the change of evacuation time and $t_{\max}$ dependency plot shape, for different values of critical mass. Because the main aspect here is, that simulation which makes $cm_{\min}$ completely independent of $t_{\max}$ can't be done. A value of $t_{\max}$ has to be assumed to make the algorithm going and individuals choose an exit. That is why one has to check the influence of $cm_{\min}$ on evacuation time with reference to $t_{\max}$.

When it comes to higher values of $t_{\max}$, high value of $cm_{\min}$ makes evacuation time a little bit longer. Actually for the highest values of $t_{\max}$ it is the time for evacuation with only one exit. Because of high $cm_{\min}$ those individuals, which don't want to stay in queue (average $t_{\max}$) and try to find another exit than e_1 (almost all of individuals early on are close to that exit), immediately are attracted by big $cm_j \supset cm_{\min}$ of e_1 queue.

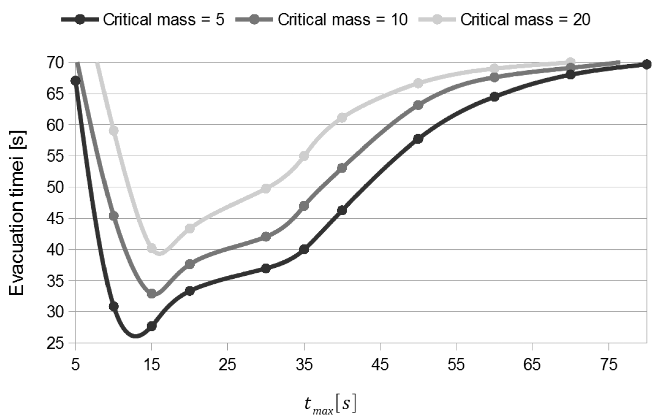

Fig. 6. Evacuation time plot characteristic for various values of critical mass

The bigger $cm_{\min}$ is, the longer evacuation lasts, with constant value $t_{\max}$. In the Fig. 6 function of evacuation time is going higher with higher value of critical mass. High critical mass cause that it is much more difficult to make crowd split into groups. It is even harder to split, when at the beginning almost all of individuals are set close to one of exits. When it is so, quickly there occur big critical mass in the queue of e_1, which has a great influence on the rest of the crowd.

Described situation is true for significant values of $cm_{\min} \geq 5$. Quantity of individuals equal 5 or more, gathered in the same place or moving together towards the same direction, can be stated as significant, because it can be easily recognized by a single individual. But when critical mass is extremely low (in Fig. 5 $cm_{\min} = 1$), it makes rather noise than order in the organization of the crowd, and that's why for such low values of critical mass, evacuation time is becoming longer.

Providing the effect of a critical mass in the algorithm additionally to $t_{\max}$ parameter, results of evacuation effectiveness may be even better than with $t_{\max}$ only. While big values of $cm_{\min}$, which reflect that individual reacts only for numerous groups of other ones, takes some kind of stagnation to individual's behaviour, rather small (but not too small) values of $cm_{\min}$ cause, that effectiveness of evacuation is better. Not only single individuals are able to attract other ones ($cm_{\min} = 1$), but also they manage to form groups and when those groups find a new exit, they are able to attract individuals from greater distance or from other groups (providing that t_{ij} values for those individuals allow them to move to another exit, what is for them more profitable than staying in current queue).

The best found solution, taking into consideration both parameters, $t_{\max}$ and $cm_{\min}$, is 40% better than best solution found for $t_{\max}$ only (Fig. 5). The load of exits for that solution during whole evacuation time presents Fig. 7. As it shows, for e_2 and e_3 there is a short period of time at the beginning, necessary for crowd to find those exits. For the exit e_4 that period is even longer, but for all of exits, after they are found by individuals, their bandwidth is being well exploited by the end of the evacuation.

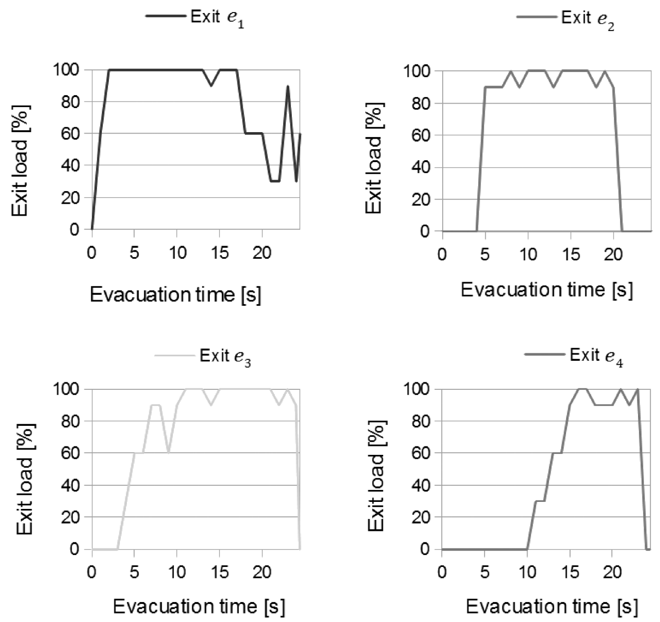

Fig. 7. Time-varying load of exits for the shortest evacuation time found

Second part of experiments was focused on exits deployment. At first it was investigated, how many exits there should be not to make them too many but enough to use them effectively, and what are best locations for them in test area (Fig. 4).

With those ends in view, first step was to determine the effectiveness of adding more exits. In other words, it was checked, how much one more exit shortens the evacuation time. Therefore, a crowd of 250 individuals was distributed in the test area completely evenly. Parameters of algorithm were assumed those, for which best solution of test area evacuation was found, $t_{\max} = 13$ s and $cm_{\min} = 5$. Exits were situated in the middle of the walls, each one in the different wall and two exits were placed. Then evacuation times were gathered. Results are presented in Fig. 8.

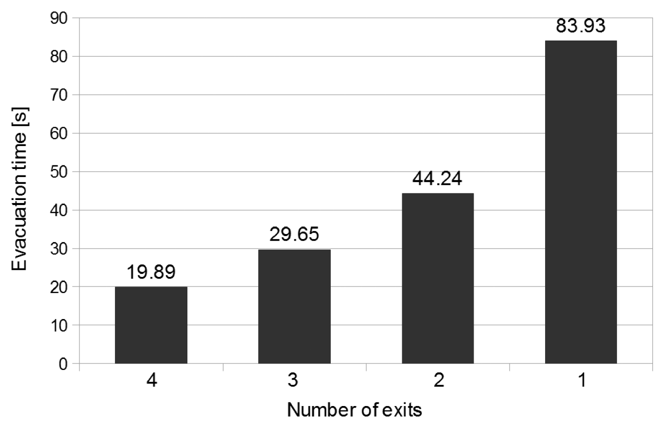

Fig. 8. Simulation area with marked crowd and exits

When it comes to four exits distributed evenly, the achieved result is even noticeably better than that, which was obtained for four exits in the test area configuration (Fig. 4), although the only difference was in location one of exits. Therefore it can be said, that more regular distribution of exits brings better results. Apparently, the worst result was obtained for single exit. The reason is not only, that the exit is just one, but for more than one exit crowd (assuming proper parameters of $t_{\max}$ and $cm_{\min}$) is able to well balance the loads of all exits. There is a very good result especially for two exits, because it improves significantly the result for one exit and simultaneously more exits do not bring such relevant progress. Nevertheless consulting even distribution of the crowd and the size of test area it has to be noticed that for not regular distributions of individuals or bigger sizes of areas there will be an initial time of reaching all the exits before they can be used, so in those cases for three or more evenly distributed exits there will be more significant progress with regard to two of them.

After it was shown, that the use of two exits brings best progress for rooms and areas of a typical size, the last question arises – what are best and worst locations for exits and what can be said about hints for exits deployment. For that reason there were some typical, standard exits configurations prepared to make tests of crowd evacuation, once more evenly distributed and consisted of 250 individuals. Those prepared areas are shown in Fig. 9.

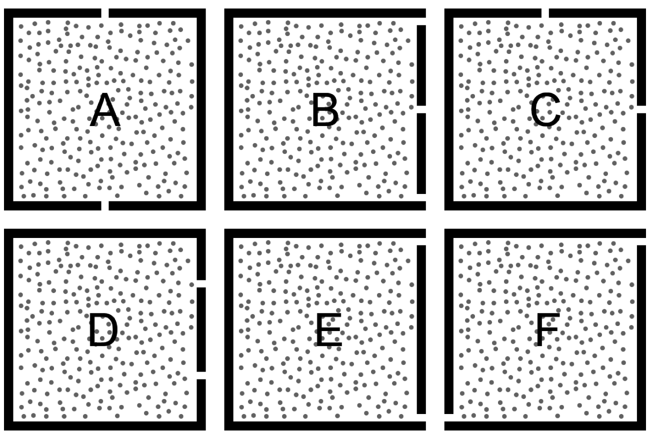

Fig. 9. Simulation area with marked crowd and exits

The aim was to check the efficiency of exits in opposite walls, in adjacent walls, a few exits set on the same wall and if position of exit in the corner of the room is correct. In all the cases there were two exits applied, excepting case B, in which there were three of them, representing a typical kind of conference or audience room. The results of that experiment are presented in Fig. 10.

Either for the case A or B, or C results are very close. When it comes to the case A and C it can be explained by the symmetry of exits placement, which in the ncase C is only a little bit dysfunctional. As far as the case B with its three exits is concerned, the result seems to be rather poor. When all exits are located in the same wall, an additional third exit does not improve the result at all. The reason is insufficient dispersion of exits. They are not enough separated from one another. The confirmation of that statement can be found in the case D, where two exits are also close to each other and the result is average, visibly worse than in cases A and C. Second reason of bad result for case B are exits near corners. What can be seen for cases E and F, which are various configurations for two corner exits, they are worst cases among all analysed. The efficiency of the case E is comparable to result of single exit (Fig. 8). Therefore location of exit near the corner trims down more than a half of its efficiency. Then, the result obtained in the case F is the worst, even if there is a full symmetry of exits deployment, because exits are far away from each other and a crowd is unable to balance the load effectively.

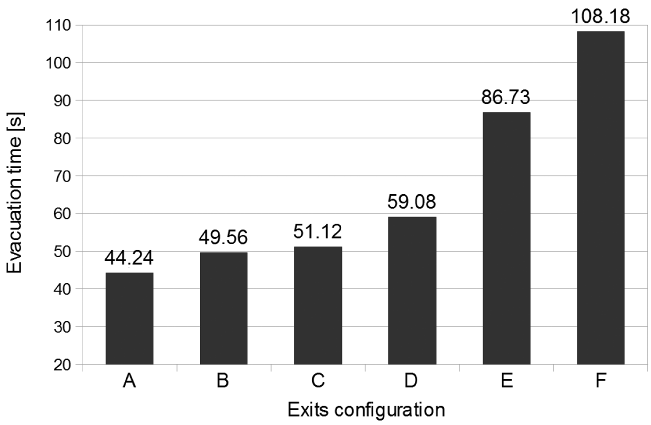

Fig. 10. Simulation area with marked crowd and exits

5. Summary

In this paper the process of an exit selection by the crowd during evacuation was studied. The proposed model is based on a cockroach algorithm with emergent swarm behaviour. Experiments include the influence of model factors different values on evacuation time and the most effective exit number and deployment research.

To sum up above experiments and their results, efficient exits deployment referring to an exit selection by the crowd during evacuation should take into consideration four main aspects and factors. The first one is symmetry. Exits ought to be located symmetrically, as much as it is possible, what can be explained that parts of a room or an area analysed, which are potentially associated with each exit, should be equal. The second issue is an average distance between exits, watching from the viewpoint of an individual, what is strictly connected with a deviation of distance to the nearest exit for each point of an area (therefore areas should be not too elongated). That issue is strongly connected with load balancing. Third aspect is a suitable separation of exits from one another, so that individuals in a crowd can easily choose a proper exit for themselves and so that there is no problem with collision of groups, waiting in queues to different exits. Finally, the fourth point is an easy access. Exits should be without any trouble accessible from any side. Under no circumstance they can be situated in the corners or near them. It can significantly cut down their efficiency and prolong the time of evacuation.

Those four assumptions may be fulfilled in some measure, depending on an evacuation area size, shape and other factors. Also in almost any case symmetry, distance, separation and easy access interpenetrate one another and it is impossible to optimize all of them separately. There always has to be found a solution, which is a good balance of those four factors and which should provide quick and efficient evacuation of the crowd.

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