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SIMULATION MODELLING AND ANALYSIS OF CROWD EVACUATION BY UTILIZING EVOLUTIONARY STABLE STRATEGY

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Abstract. *Crowd and evacuation management has been active areas of research and study in the recent past. Various developments continue to take place in the process of efficient evacuation of crowd in mass gatherings. This article is intended to provide an analysis on crowd evacuation models based on the game theory approach. There will be interaction among evacuees in which the evacuees tend to be either cooperator or defector in order to move towards desired path. This paper analyzes in detail the pure and mixed strategy of Nash Equilibrium (NE) and Evolutionary Stable Strategy (ESS) as a result of different types of interaction among evacuees under different scenarios that possibly could happen during normal and emergency evacuation. We found out that due to the higher cost of interrupting than the value of benefit able to move, the proportion of defectors playing the ESS will decrease compared to the proportion of cooperators playing the ESS.*
Keywords: Evacuation simulation, Game theory, Evolutionary Stable Strategy

1. **Introduction.** Various research developments have been proposed in the process of safe and efficient management of human crowd during large scale events like Hajj pilgrimage, mega festivals, sporting events as well as regular pedestrian flooded public places such as shopping areas, and underground subways. For crowd safety, it is very important to study the behaviour of the crowd and simulate the crowd evacuation. At present, a large volume of research concentrates on the crowd simulation tools which are implemented prior to gathering of a large crowd to enable the mitigation of crowd disaster by identifying the critical location [1] where possible congestion, clogging and crowd disaster may occur. It is vital to predict the area where the crowd congestion may occur during any particular event in order to provide safety to the crowd [2]. Although the organizers of large gatherings might have done the needed preparation, it is difficult to anticipate the behaviour of crowd during an event that may lead to possible crowd disaster. Hence, it is essential to analyze the behaviour of the crowd in order to provide safe and better evacuation flow for the crowd.

During a typical evacuation scenario, evacuees tend to cooperate or defect with another evacuee in order to move towards the desired path. This paper analyzes in detail the interaction among evacuees under different scenarios that possibly could happen during normal and emergency evacuation. We describe the Evolutionary Stable Strategy (ESS) for different types of cases. Evacuees achieving equilibrium by adopting ESS could produce smooth flow while preventing any mutation strategies may lead to crowd disaster. The paper is organized as follows. Section 2 describes the previous work pertaining to crowd behaviour, while Section 3 elaborates on game theory evacuation model. Finally, in Section 4, the full result is discussed before the paper is concluded pointing out possible future research.

2. **Related Work.** Crowd dynamics during evacuation scenario can be discovered via macroscopic [3], mesoscopic [4] and microscopic [5] models. Macroscopic models neither make distinctions between individual pedestrians nor describe their individual behaviour but consider the pedestrian flow in terms of density, average velocity and flow patterns. In contrast, microscopic models consider individual pedestrian behaviour separately. The pedestrian behaviour in this model is often described by their interactions with other pedestrians in the system. However, mesoscopic models view a small group of people in the same environment and every group has its own identical behaviour. This research focuses on the microscopic view since collective behaviour of each crowd will affect the movement and behaviour of the whole crowd. Game theoretic evacuation model is verified as a sophisticated model to study the crowd dynamics of individual interaction entailed in microscopic models [6]. This is the reason why recently there have been various research contributions that emphasised to describe the behaviour of crowd during evacuation scenarios with the aid of game theoretic approaches.

Game theory investigates and formulates mathematical models that deals with the decision making of interacting players. Game theory can well describe the day to day activities of individuals in which the players have certain set of rules in order to interact with every other player. Although game theory has been utilized to describe economical, biological computational and political phenomena, the scope of game theory is large that could encompasses our daily activities. For example, in a situation where a car is coming opposite to another car in a single lane road, there are several actions that the players could take in this particular situation which are either swerve or continue straight. The set of preferences that could be embedded with each action is known as payoff functions as displayed in Table 1. However, the payoff that one player will receive depends on the action of the opponent. Pure strategy Nash Equilibrium (NE) of this game is to play swerve when the other is playing continue and vice versa. However, there exists another equilibrium in this game which is a mixed strategy of swerve and continue by a probability of $(c/(b+c),\, b/(b+c))$, where b represents the benefit of arriving at preferred destination while c represents the cost of crash. Failure of achieving equilibrium will lead to each player in getting a zero outcome or have to bear the cost of crash.

TABLE 1. Single lane road game

Player 1 / Player 2	Swerve (x)	Continue (y)
Swerve (x)	0, 0	0, b
Continue (y)	b, 0	$-c$, $-c$

Game theory for evacuation model was started in [7], where the authors implemented game theory model for exit selection during evacuation scenario. They have studied competitive behaviour by assuming that evacuees are selfish in a non-cooperative game. One of the drawbacks of the model is that they have assumed that all evacuees are rational during the fire scenario, while in real cases, most of the evacuees tend to be panic. In [8], the authors also presented exit selection model for evacuation based on evacuees' best response. They have added the patience parameter in order to study minimal time for the evacuees to find the alternate exit. They have found that patience parameter affects the time required to achieve equilibrium.

Another interesting work using game theory for evacuation was done in [9] and [10]. The authors have combined game theory with floor field cellular automata where only one evacuee can go through the exit and each person can take one of the three possible strategies, 'polite', 'normal' and 'vying'. The payoff table for these strategies can be seen in Table 2. Pure strategy Nash Equilibrium of this game is to play 'polite' when the other is playing 'vying' and vice versa. Another pure strategy Nash Eqilibrium is to

Table 2. Payoff table as in [9]

Player 1 / Player 2	Polite	Normal	Vying
Polite	0, 0	0, b	0, b
Normal	b, 0	$b/2$, $b/2$	0, b
Vying	b, 0	b, 0	$-c$, $-c$

play 'normal' when the other is playing 'vying' and vice versa. A probability of mixed-strategy Nash Equilibrium is $(0,\ 2c/(2c+b),\ b/(2c+b))$, which means zero for 'polite' strategy, $2c/(2c+b)$ for 'normal' strategy and $b/(2c+b)$ for 'vying' strategy. They have included herding coefficient also in order to study the tendency of evacuees to follow others. They had found that high herding coefficient will lead to 'vying' strategy to grow in the crowd. Other related work of evacuation simulation via game theory can be found in [11-14]. However, based on our research, none of these work utilized ESS to describe the interaction that occurs among crowd. Research in the area of evolutionary game theory based evacuation models is vital to provide insights in order to better understand the crowd behaviour during emergency scenarios. It is a well-known fact that during panic scenarios, the distorted crowd could evolve to new situations that possibly could lead to crowd disasters such as stampedes. Hence, this work attempts to utilize ESS in order to analyze the possible interactions that could occur among evacuees in normal and emergency evacuation situations.

3. Game Theory Evacuation Model.

3.1. **2×2 evacuation model.** In a 2×2 evacuation game, there are only two different strategies that can be adopted by evacuees which are cooperate (C) and defect (D). The payoff for these strategies are shown in Table 3. When the cooperator meets another cooperator, sometimes one of the cooperators could get to the next move, while another stops there and vice versa. When the evacuee is able to move, the payoff is b which refers to benefit in going to next move. However, the payoff is $b/2$ due to equal probability in getting to the next move by both cooperators. When the cooperator meets defector, the defector for sure will go to the next move without any interruption by cooperator, that is the reason why cooperator will attain zero payoff which means not able to move, while the defector will get the payoff b. Interestingly, when the defector meets another defector, both of the defector will try and push in order to move. Sometimes one of the defector will win which means able to move and getting payoff b, while the loser is not able to move. Apart from unable to move, the loser will bear the cost of interrupting another defector, $-c$ which means loss of energy and possibility of getting injured. However, the payoff is $(b-c)/2$ due to equal probability of winning and losing by both defector. Now, let us analyze the pure strategy NE, mixed strategy NE and ESS for different scenarios of crowd.

Table 3. Payoff table for 2×2 evacuation game

Evacuee 1 / Evacuee 2	Cooperate (C)	Defect (D)
Cooperate (C)	$b/2$, $b/2$	0, b
Defect (D)	b, 0	$(b-c)/2$, $(b-c)/2$

Case A: Value of benefit going to next move more than the cost of interrupting. First, let us analyze the case where the value of benefit going to next move is far more than the bearing cost of losing due to interrupting, which is $b \geq 2c$. The possibility of this scenario would occur when the evacuee value of reaching the destination is far more than the cost of losing due to interruption with others, for example, when the evacuees try to evacuate as fast as possible due to the spreading of fire near them. Another example is more applicable to the flow of crowd, which is when the crowd is spiritually motivated, crowd try to get near to the holy *black stone* during the ritual act of circumambulation the *Kaaba*. Since overall payoff is $DC > CC > DD > CD$, this type of interaction mimicked the *prisoner's dilemma (PD) game*. This type of game has the symmetric strict NE which is the defect strategy. In other words, defect strategy also leads to the ESS. Let us examine stable strategies in a group of crowd which has a population of 100000. For the purpose of simulation, initially it is set half of the crowd will be defector and another half will be cooperator. The crowd are able to improve their strategies based on their experience of previous interactions. The simulation is done using GameBug Simulation Software [15]. As expected, approximately just after 50 interactions, defect strategy becomes dominant and it is stable enough to prevent the mutation of other strategies as in Figure 1.

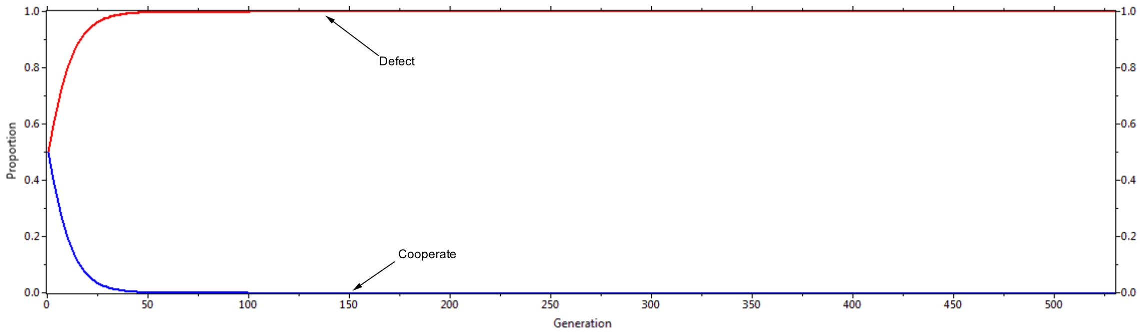

FIGURE 1. Result of the crowd Evolutionarily Stable Strategies (ESS) for $b \geq 2c$ (Red: Defect, Blue: Cooperate)

For the case where the value of benefit going to next move is a little more than the bearing cost of losing due to interrupting, which is $c < b < 2c$. This scenario is possible to happen when the evacuees' value of reaching the destination is more than the cost of losing due to interruption with others. Normal evacuation scenario or normal crowd flow during large gathering is a typical example for this type of scenario. Similar to the previous scenario, the defect strategy is the strict NE which is also ESS. However, crowd needs more interaction (100 interactions) as compared to the previous scenario before achieving equilibrium state where the defect strategy becomes dominant as shown in Figure 2.

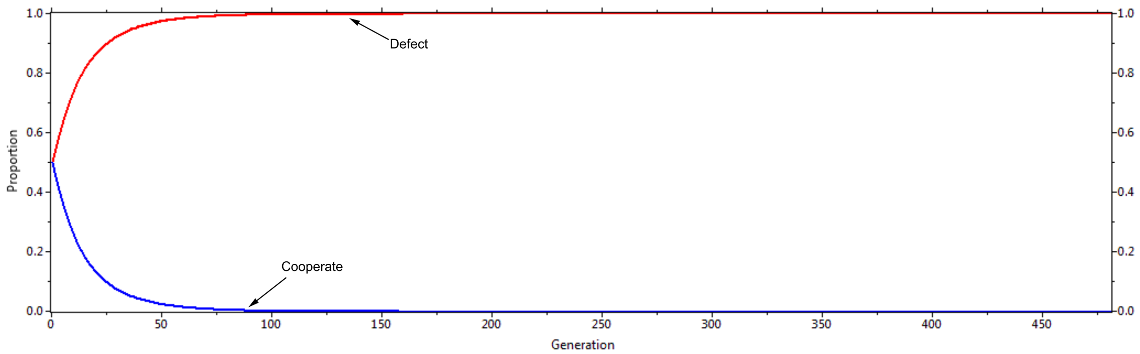

FIGURE 2. Result of the crowd Evolutionarily Stable Strategies (ESS) for $c < b < 2c$ (Red: Defect, Blue: Cooperate)

Case B: Value of benefit going to next move less than the cost of interrupting. This scenario which is mathematically $b < c < 2b$ could occur in the scenario of evacuation or crowd flow inherent on a denser population where the evacuee feels uncomfortable of being aggressive to move, rather, the crowd will start to cooperate in order to achieve smooth flow of crowd. Since overall payoff is $DC > CC > CD > DD$, this type of interaction deemed to be like the *chicken game*. Pure strategies of NE are as follows: ('defect', 'cooperate') and ('cooperate', 'defect'). A probability of mixed strategy NE is $(1 - b/c,\ b/c)$ where $1 - b/c$ refers to the 'cooperate' strategy and b/c refers to the 'defect' strategy. Since the pure strategy NE is not a symmetric NE, the ESS is a mixture of probability same as mixed strategy NE. The mutation of defect or cooperate strategy gets lesser payoff when they meet the larger population of crowd playing other strategies causing the mutation strategy to die out. The simulation example of results for the typical case of $b = 8$ and $c = 10$ is shown in Figure 3 where the equilibrium is achieved when 20% of crowd is playing cooperate strategy.

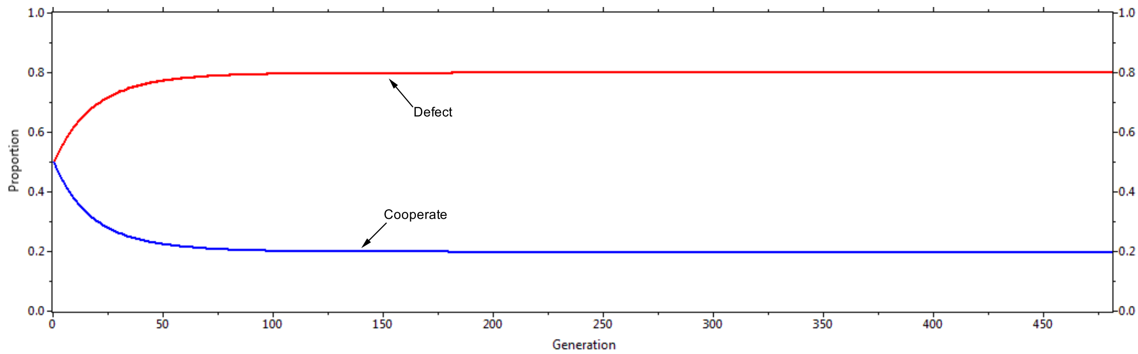

FIGURE 3. Result of the crowd Evolutionarily Stable Strategies (ESS) for $b < c < 2c$ (Red: Defect, Blue: Cooperate)

When the crowd get denser than the previous scenario, it can be assumed that evacuees would prefer to cooperate rather than playing defect strategy. Here, the scenario refers to the cost of interrupting at least double of the benefit able to move. Same as the previous scenario, the ESS is a mixture of probability of $(1 - b/c,\ b/c)$ where $1 - b/c$ refers to cooperate and b/c refers to defect strategy. The example of results for $b = 8$ and $c = 20$ is shown in Figure 4 where the equilibrium is achieved when the 60% of crowd is playing cooperate strategy.

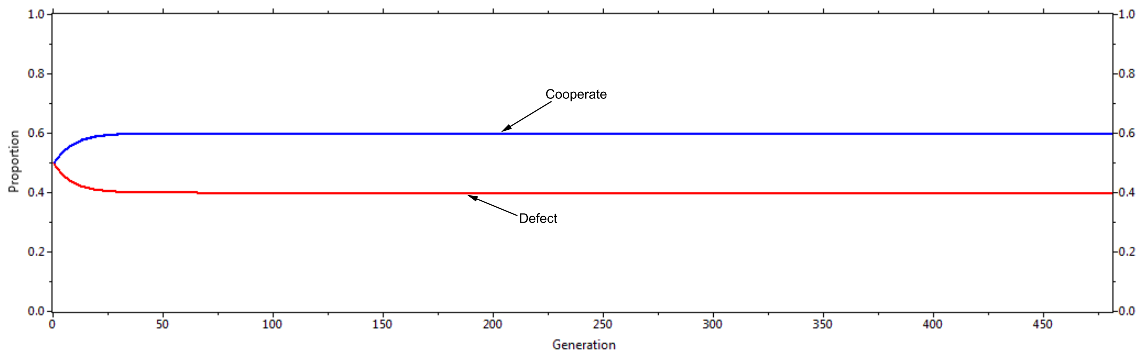

FIGURE 4. Result of the crowd Evolutionary Stable Strategies (ESS) for $b < 2c$ (Red: Defect, Blue: Cooperate)

In a 2×2 evacuation model, the *prisoner's dilemma* type of game is observed when the value of benefit goes to next move more than the cost of interrupting. As expected, defect strategy becomes dominant as it is ESS and causes other strategies to die out when the crowd achieved equilibrium. In contrast to this, the *chicken* type of game emerges when the value of benefit goes to the next move less than the cost of interrupting. This type of game shows ESS as a mixed strategy of cooperate and defect and hence ESS will become dominant when equilibrium is reached.

3.2. **Multiplayer evacuation model.** During evacuation, practically it is more than two players who could compete for achieving the desired position. Normally, Moore neighbourhood scheme in [13] and Von Neumann neighbourhood scheme in [9,10] were utilized in order to model the multiplayer evacuation scenario. However, it is more practical that the evacuees normally compete with another four neighbours to move to wished position as displayed in Figure 5. The interaction can be either $CCCCC$, $DCCCC$, $DDCCC$, $DDDCC$, $DDDDC$, or $DDDDD$ combination of evacuees.

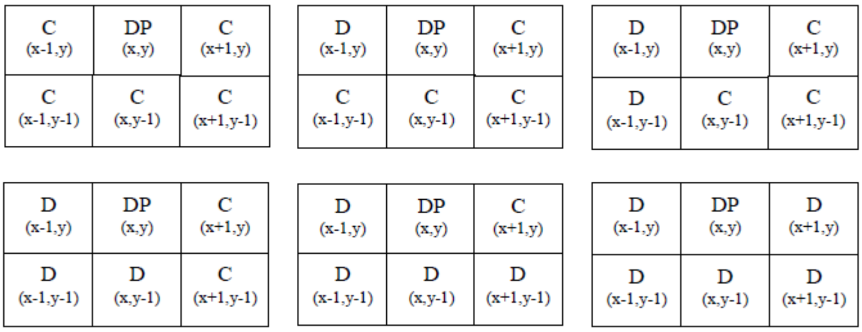

FIGURE 5. Several sets of interaction among evacuees (C: Cooperator, D: Defector and DP: Desired Position)

Payoff table for this type of interaction is shown in Table 4. The payoff shown only for the evacuee 1 since all other evacuees will get the identical payoff for the similar type of interaction. For the case of $b > c$, 'defect' strategy is a strict NE and it is also an ESS. For $b \leq c$, since no pure strategy NE, the mixed strategy between cooperator and defector will take place for NE and ESS similar to interaction of 2×2 evacuation model. However, the percentage value of cooperator and defector depends on the value of cost of interruption and the benefit of moving to desired position.

TABLE 4. Payoff table for the multiplayer evacuation game

Evacuee 1 / Evacuees 2	$CCCC$	$DCCC$	$DDCC$	$DDDC$	$DDDD$
Cooperate (C)	$b/5$	0	0	0	0
Defect (D)	b	$(b-c)/2$	$(b-c)/3$	$(b-c)/4$	$(b-c)/5$

4. **Discussion and Conclusions.** We perceive that achieving ESS in any typical crowd flow will lead to smooth and better flow. Ultimately, it will lead to safer and faster evacuation time as a result of smooth flow. We found out that the ESS of cooperate strategy will increase in the crowd due to the higher cost of interrupting than the value of benefit able to move and vice versa as shown in Figure 6. Why do we need ESS instead of NE? ESS is better than NE because it can prevent from the mutation strategy. During panic scenarios, the distorted crowd could evolve to new postulates that possibly could lead to crowd disasters such as stampedes. However, if the majority of the crowd is playing ESS, then, the mutation strategy would die off due to lower payoff that they attain. Hence, the crowd is safe from possible crowd disaster due to mutation strategy. Main contributions of this research are as follows: i) analysis of different types of interaction among evacuees that could occur during evacuation scenarios is presented, ii) comparison of NE and ESS as a decision entity in the various crowd scenarios is offered, and iii) a new scheme for multiplayer evacuation model together with its utility functions and analysis of NE and ESS has been proposed.

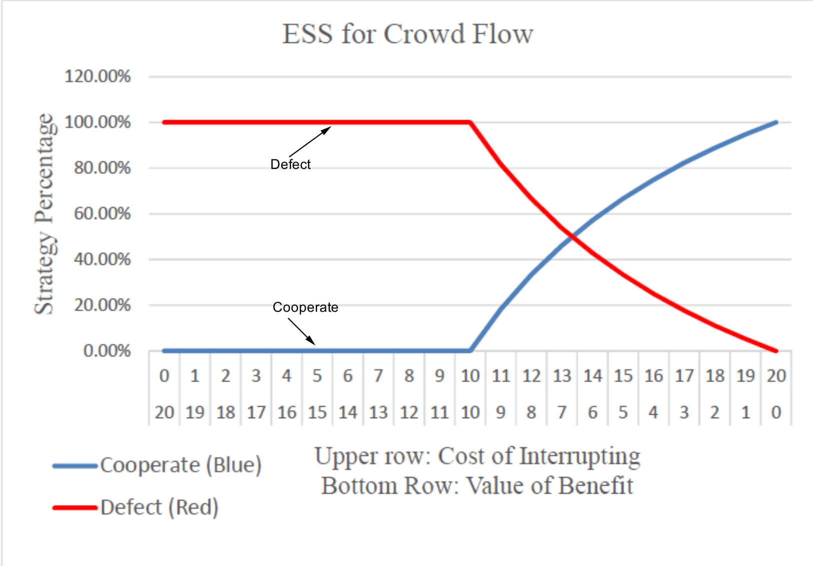

FIGURE 6. ESS for 2×2 crowd flow

Current work focuses on analyzing the NE and ESS for different types of interaction of evacuees without relating to simulation of evacuation scenarios. The future work includes: analyzing evacuation time for ESS, including more strategies such as assessor and retaliator and combining Cellular Automata with ESS to simulate evacuation model.

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