Available online at http://scik.org
Commun. Math. Biol. Neurosci. 2022, 2022:91
https://doi.org/10.28919/cmbn/7553
ISSN: 2052-2541

STUDY OF AN OPTIMAL CONTROL MODEL FOR THE PANIC PROPAGATION IN A FLYING AIRCRAFT

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Abstract. The aim of this paper is to study a discrete mathematical model of panic spreading on an airplane inspired by SIRS model, and the optimal control strategies, applied to reduce the number of panicked passengers during the flight. The population is divided into three compartments: Panic-prone panicked, and recovered passengers. Two control strategies were used, which are psychological therapies, applied by trained flight personnel, to both susceptible and panicked passengers. The discrete-time Pontryagin maximum principle was used to characterize the optimal controls. All numerical simulations were performed using MATLAB. The obtained results demonstrated which of the strategies is effective.

Keywords: aircraft; aviation; safety; panic; optimal control; Pontryagin's maximum principle; discrete time.

2010 AMS Subject Classification: 49M25.

1. INTRODUCTION

Air travel is now the most common and widespread means of transcontinental and intercontinental transportation, as it can reach all corners of the world in a matter of hours. Although the aviation system is relatively a recent form of transportation. Nevertheless, emergencies (bomb threat, hijack, engine failure, etc.) do occur and create a sense of panic among the passengers

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Received June 15, 2022

throughout its history. The phenomenon of fear of flying is indeed considered to be ubiquitous nowadays.

Generally, panic is understood as a general fear characterized by its instantaneous transmission among groups of individuals, triggering a true state of crisis characterized by a general emotional reaction that inevitably leads to disorganization and may develop into an extreme disorder. Furthermore, it is commonly accepted that in a state of panic, all human actions lead to reverse outcomes, thus increasing the danger to one's own life and the lives of others. A "panicked person" conjures up an image of a helpless person whose behaviour creates harmful effects. However, these widespread ideas associated with panic may not necessarily reflect the reality of the situation. The panic may potentially result in disorientation and put individuals in a state of extreme stress which affects the brain's primitive centre, the Amygdala [2], and triggers the fight or flight response which is a physiological reaction that occurs when we are in the presence of something mentally or physically terrifying. In emergency situations, humans enter into panic due to unpredictable factors [14]. These emotions are contagious and rapidly spread through a crowd. Therefore, panic emotions, as a natural uncontrolled process, can spread from one individual to all air passengers [18, 17].

In the time period from 1990 to 2013, the human component played a key factor in 83% of the number of aviation accidents [11]. However, not all aviation accidents are the result of error or mishandling, as many of these were committed without necessarily resulting in a disaster [12]. Over the last decades, considerable attention has been devoted to hazardous incidents in air transport; they are conceived as substitutes for actual safety measurements. Indeed, the notion of risk refers to the mental ability to identify the danger associated with a situation; to do so one needs a thorough analysis of each situation as well as of the individual's personal behavioural skills [13]. Furthermore, the control of situations of risk is vital in the context of Air Transport, insofar as a risk can be determined according to the level of awareness that any crew has at that particular juncture. Therefore, any overestimation or underestimation of risk would lead to variable degrees of danger.

A high level of risk perception requires firstly an errorless assessment of the situation, secondly an ideal way of directing problematic situations, and finally reacting in an adequate manner. However, nowadays, various considerations have influenced human risk perception; according to statistics, 10% of air passengers are uncomfortable due to the fright of being on an aeroplane, while 40% experience a whole range of fear, anxiety, terror, panic attack [21, 22]. This "aeroplane stress" is generated from the loss of control of unusual external conditions, bearing in mind the fact of being trapped at an altitude of ten thousand meters, when it is minus fifty-five and the atmosphere is thin. Thus, the most intense fear occurs onboard during certain phases of the flight (take-off turbulence, air holes, bad weather ...). Further incidents of panic status are utterly connected with past experiences which can trigger anxiety problems. The negative background of flying is usually fixed in the subconscious of a person, which causes negative associations in the future; this case occurred in September 2018 to the co-pilot of the British airline EasyJet, an emergency situation occurred when the plane landed and was at an altitude of 30 feet (9.4m). At that point, warning instructions came from the aircraft dispatcher telling the plane not to land, and to go for a second circle as strong winds shifted the airliner to the edge of the runway. The next day the same pair of pilots flew from Glasgow to Stansted, yet when approaching Glasgow, the co-pilot began to suffer from anxiety, could not continue to control the plane and left the cockpit as a consequence of a panic attack.

The spread of panic in an aircraft may cause detrimental impacts on the safety of passengers, any disorder can lead to an emergency landing at the nearest airport to prevent possible damage. One of the most tragedic incidents illustrating serious outcomes of panic propagation in an aeroplane is the Lockheed L airliner-1011 Saudi Arabian Airline Tristar 200. The tragedy occurred on August 19, 1980, when the aeroplane left Riyadh airport; a few minutes later, a fire had begun to break through to the rear of the cabin. The situation worsened dramatically after the spread of the panic from the cabin [10]. The commander on the speakerphone asked everyone to stay in their places as all passengers were panic-stricken. Meanwhile, pilots warned the airport to return due to the smoke. However, travellers could not control their fear so they leave their seats and consequently, the plane's alignment was disrupted. Fortunately, the aircraft landed safely, yet did not stop directly on the runway, it turned onto the taxiway, which took almost three more minutes of precious time due to the extreme stress of the crew. At the moment when an immediate evacuation should be done, none of the emergency doors was opened and people were found heavily concentrated at the forward exits. In the meantime, the smoke penetrated the passenger compartment killing all 301 people on board, 287 passengers and 14 crew members. The risks are considerably reduced if some passengers are given detailed instructions on how to operate the exits and if other passengers are instructed to support each other in an emergency.

However, a close examination of human behaviour in life-threatening situations reveals that the perception of panic is not always correct, as shown in many interviews conducted by the National Opinion Research Center (NORC) with many disaster survivors, giving as example: plane crashes, building fires and mine explosions. Quarentelli, a NORC investigator and specialist in the psychological aspects of disaster behaviour, revealed that panic flight has many characteristics [9]: the flight response is triggered but there is no danger about to happen. Although the existence of the overwhelming threat, the flight is the most possible and effective action, hence, terrified individuals may act differently according to many determinants, they could choose rather run, swim or scrawl. Two major factors determine panic-stricken passenger's direction: the first one revealed that a recent habit or behaviour tends to guide air passengers to a familiar gate, usually similar to the one they boarded through; secondly passengers appear to follow the direction of others. Moreover, the strongest social bonds could be easily broken such as children's abandonment by mothers, while others may injure or kill for the sake of survival, ignoring the serious consequences of their actions.

From the information mentioned above, it is concluded that the plane is considered a favourable environment for panic propagation, this fact presents a serious danger to the aircraft's users in case of mis-control. Besides complications of delays and even cancellation of a flight for some reasons of security, sometimes emergency situations may force the plane to land at the nearest airport to avoid any exceptional situations. Unfortunately, all these incidents affect both safety and the economy. The latter is affected significantly depending on the flight phase, as an emergency landing generates a minimum delay of 30 minutes up to 120 minutes according to several parameters as (flight time to the nearest authorized airport, taxi time to the stand, time to disembark the panicked passengers...) which engenders additional costs for the airline. Additionally, a 30-minute delay in the parking area costs between 490 and 3420 euro, while taxiing fees are between 650 and 4720 euro and en route between 710 and 7560 euro depending on the aircraft type without reactionary costs [1].

Several studies have been conducted on the spread of panic within different environments: Rongyong Zhao [15] analyzed the psychology and the panic-stricken crowd's behaviour by virtue of a new non-linear dynamic model of panic propagation in crowd fusion, evolved from the bullet collision principle. In [24], a model emphasizing the process of evacuation of panicky passengers was submitted, based on the theory of multi-agent systems. Another propagation model of panic buying behaviour was built by Peihua Fu, utilizing the classic simplest SIR model, including the study of people conformity, individual needs, released time of external information, and the interaction number [20]. Mehran [29] proposed a new CALM model (for constrained linear movement of individuals in a crowd), designed to simulate movement in narrow linear passageways, into an aircraft for instance, and Tianlu Mao [27] introduced a panic model, named PPIB (Panic, Propagation and Influence on Behavior) aimed at examining panic behaviours on a dynamic crowd especially for dangerous situations, demonstrating several phenomena including panic propagation. Namilaea [8] formulated a pedestrian movement model based on social forces including dependence of self-propulsion terms intended for evaluating trajectories and contacts between people in several aircraft configurations. Jianyang Li [28] describes a dynamic transmission model of passenger panic concerning underground cars taking into account official information, operating a combination of system and transmission dynamics beside epidemic models, while Nuria developed another model HIDAC (High-Density Autonomous Crowds) in order to simulate different types of crowds, ranging from extreme panic situations to very dense crowds under calm conditions [26, 23]. Hence, in [30], a traditional SIRS model was improved, along with passenger panic propagation characteristics in a state of panic emergencies, further aspects have been studied as the spread of information in subway emergencies using the complex transmission dynamics. The conclusion of the study stands for the possibility to reduce the panic infection ratio by dint of control strategies such as enhancing subway safety management by organizing awareness campaigns for subway emergencies without neglecting the process of controlling the number of subway passengers [16].

2. Model Description

In this section, we define a discrete mathematical model $(X)(Y)(Z)$ describing the dynamics of Panic propagation during flight.We suppose that panic may be transmitted through proximity, as seen in Figure 1. The chosen dynamics take into account only one flight with a specific numbers of passengers.

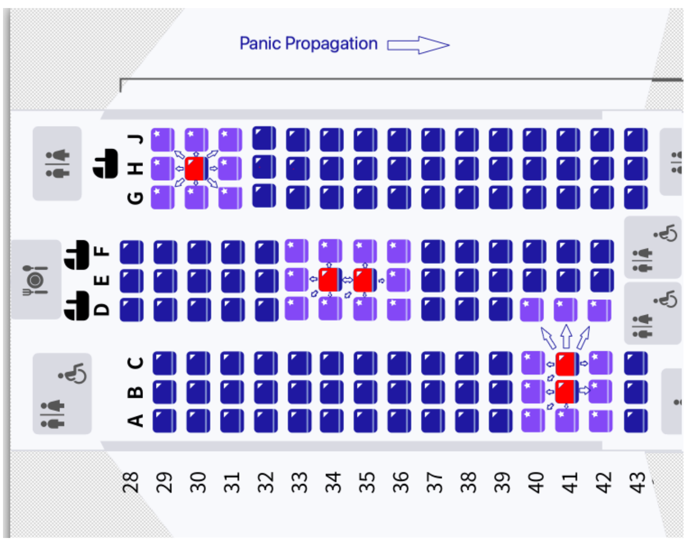

FIGURE 1. Example of Aircraft Seats Configuration

The Passengers in the model are divided into three categories: susceptible Passenger for panic $(X)_i$, panicked passengers $(Y)_i$, Recovered passengers from panic $(Z)_i$, the model is described by the following discrete system:

$$
\begin{aligned}
X_{i+1} &= X_i - \beta X_i Y_i - \mu X_i + \theta Z_i \\
Y_{i+1} &= Y_i + \beta X_i Y_i - \sigma Y_i \\
Z_{i+1} &= Z_i + \sigma Y_i + \mu X_i - \theta Z_i
\end{aligned}
\tag{1}
$$

subject to non-negative initial conditions.

TABLE 1. The meaning of the compartments considered in the model

Compartments	Meaning
X_i	represents the number of passengers susceptible to panic.
Y_i	represents the number of panicked passengers .
Z_i	represents the number of Recovered Passengers and none susceptible.

TABLE 2. The meanings of the parameters considered in the model

Parameters	Meaning
μ	The rate of passengers switching from susceptible to non-susceptible.
β	The rate of passengers becoming panicked
θ	The rate of passenger who became susceptible
σ	The rate of passengers recovred from panic

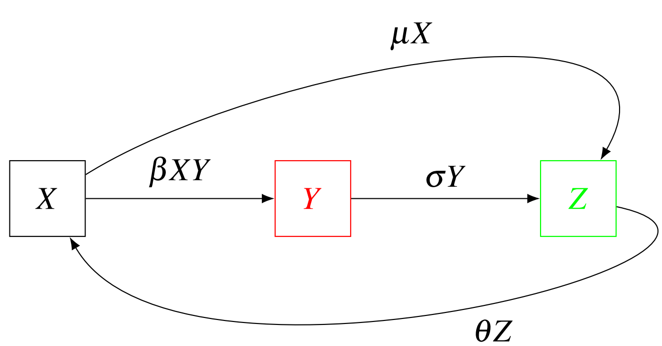

FIGURE 2. Graphical representation of the proposed model

3. The Optimal Control Problem

In this section we introduce the optimal Control problem using some control

$$
\begin{aligned}
X_{i+1} &= X_i - \beta X_i Y_i - \mu X_i + \theta Z_i - \varepsilon_1 u_i X_i \\
Y_{i+1} &= Y_i + \beta X_i Y_i - \sigma Y_i - \varepsilon_2 v_i Y_i \\
Z_{i+1} &= Z_i + \mu X_i + Y_i \sigma - \theta Z_i + \varepsilon_1 u_i X_i + \varepsilon_2 v_i Y_i
\end{aligned} \tag{2}
$$

where X_0, Y_0 and Z_0 are non negative.

Minimizing the following cost

$$
J(u,v) = \sum_{i=0}^{T} (\Psi_1 X_i + \Psi_2 Y_i - \Psi_3 Z_i) + \sum_{i=0}^{T-1} (\frac{\beta_1}{2} u_i^2 + \frac{\beta_2}{2} v_i^2) \tag{3}
$$

where, Ψ_1 , Ψ_2 and Ψ_3 are positive constants to keep a balance in the size of X_i , Y_i and Z_i respectively.

In the objective functional, β_1,β_2 are the positive weight parameters which are associated with the controls u_i and v_i at time i.

T is the final time.

In other words, we seek the optimal controls (u^*,v^*) such that

$$
J(u^*,v^*) = \min_{(u,v)\in U_{ad}} J(u,v), \tag{4}
$$

where $(u^{\min}, u^{\max}, v^{\min}, v^{\max}) \in]0,1[^4$

The sufficient condition for the existence of optimal controls (u,v) for the problem (2-3) comes from the following theorem.

Theorem 3.1. *There exists an optimal control (u^*,v^*) such that*

$$
J(u^*,v^*) = \min_{(u,v)\in U_{ad}} J(u,v) \tag{5}
$$

subject to the control system (2) with initial conditions.

Proof. Since the coefficients of the state equations are bounded and there are a finite number of time steps, $X = (X_0, X_1, \ldots.., X_T), Y = (Y_0, Y_1, \ldots.., Y_T)$,and $Z = (Z_0, Z_1, \ldots.., Z_T)$, are uniformly bounded for all $(u;v)$ in the control set U_{ad}; thus $J(u;v)$ is bounded for all $(u;v) \in U_{ad}$.
Since $J(u;v)$ is bounded, $\inf_{(u,v)\in U_{ad}} J(u,v)$ is finite, and there exists a sequence $(u^j;v^j;w^j) \in U_{ad}$

such that $\lim_{j\to+\infty} J(u^j,v^j) = \inf_{(u,v)\in U_{ad}} J(u,v)$ and corresponding sequences of states X^j, Y^j, and Z^j Since there is a finite number of uniformly bounded sequences, there exist $(u^*,v^*) \in U_{ad}$ and X^*, Y^*, and $Z^* \in IR^{T+1}$ such that on a subsequence, $\lim_{j\mapsto+\infty}(u^j,v^j) \to (u^*,v^*)$, $\lim_{j\to+\infty} X^j \to X^*$, $\lim_{j\to+\infty} Y^j \to Y^*$, and $\lim_{j\to+\infty} Z^j \to Z^*$,
Finally, due to the finite dimensional structure of system (2) and the objective function $J(u;v)$; $(u^*;v^*)$ is an optimal control with corresponding states X^*, Y^* and Z^* .
Therefore $\inf_{(u,v)\in U_{ad}} J(u,v)$ is achieved. □

As regards the necessary condition and the characterization of our discrete optimal control, we use a discrete-time version of the Pontryagin Maximum Principle [3] [4] [5] [6]. This principle converts into a problem of minimizing a Hamiltonian H_i at time step i defined by:

$$H_i = \Psi_1 X_i + \Psi_2 Y_i - \Psi_3 Z_i + \frac{\beta_1}{2} u_i^2 + \frac{\beta_2}{2} v_i^2 + \sum_{j=1}^{3} \lambda_{j,i+1} f_{j,i+1}, \tag{6}$$

where $f_{j,i+1}$ is the right side of the system of difference equations (2) of the j^{th}state variable at time step $i+1$.

Theorem 3.2. *Given an optimal control $(u_i^*, v_i^*) \in U_{ad}$ and the solutions X_i^*, Y_i^*, and Z_i^* of the corresponding state system (2), there exist adjoint functions $\lambda_{1,i}$, $\lambda_{2,i}$, and $\lambda_{3,i}$ satisfying*

$$\lambda_{1,i} = \lambda_{1,i+1}\left(1 - \alpha X_i(1-v_i)\right) + \lambda_{2,i+1}\alpha(1-v_i)X_i \tag{7}$$

$$\lambda_{2,i} = \Psi_2 + (1-\gamma)\lambda_{2,i+1} + \gamma(\lambda_{3,i+1} \tag{8}$$

$$\lambda_{3,i} = -\Psi_3 + \sigma\lambda_{1,i+1}(1-\sigma)\lambda_{3,i+1} \tag{9}$$

$$\lambda_{4,i} = \Psi_1 + \lambda_{4,i+1}(a - ui - X_i 2a/K) + \alpha(1-v_i)X_i(\lambda_{2,i+1} - \lambda_{1,i+1}) \tag{10}$$

with the transversality conditions at time T. $\lambda_{1,T} = 0$, $\lambda_{2,T} = \Psi_2$, $\lambda_{3,T} = -\Psi_3$, and $\lambda_{4,T} = \Psi_1$. Furthermore, for $i = 0,1,2...T-1$, the optimal controls u_i^* and v_i^* are given by

$$u_i^* = \min\left[u^{\max}; \max\left(u^{\min}, \frac{X_i\left(\lambda_{1;i+1} - \lambda_{3;i+1}\right)\varepsilon_1}{\beta_1}\right)\right]$$
$$v_i^* = \min\left[v^{\max}; \max\left(v^{\min}, \frac{Y_i\left(\lambda_{2;i+1} - \lambda_{3;i+1}\right)\varepsilon_2}{\beta_2}\right)\right]$$

Proof. The Hamiltonian at time step i is given by

(11)

$$H_i = X_i\Psi_1 + Y_i\Psi_2 + Z_i\Psi_3 + 1/2\,{u_i}^2\beta_1 + 1/2\,{v_i}^2\beta_2 + (-\beta\,X_iY_i - \varepsilon_1 u_iX_i - \mu\,X_i + \theta\,Z_i + X_i)\,\lambda_{1;i+1}$$

$$+ (\beta\,X_iY_i - Y_iv_i\varepsilon_2 - Y_i\sigma + Y_i)\,\lambda_{2;i+1} + (\varepsilon_1 u_iX_i + Y_iv_i\varepsilon_2 + \mu\,X_i + Y_i\sigma - \theta\,Z_i + Z_i)\,\lambda_{3;i+1}$$

Using Pontryagin's maximum principle [3] and setting X_i^*, Y_i^*, Z_i^*, and (u_i^*, v_i^*), we obtain the following adjoint equations:

$\lambda_{1,i} = \frac{\partial H_i}{\partial X_i}$

$\lambda_{1,i} = \Psi_1 + (-\beta\,Y_i - \varepsilon_1 u_i - \mu + 1)\,\lambda_{1;i+1} + \beta\,Y_i\lambda_{2;i+1} + (\varepsilon_1 u_i + \mu)\,\lambda_{3;i+1}$

$\lambda_{2,i} = \frac{\partial H_i}{\partial Y_i}$

$\lambda_{2,i} = \Psi_2 - \beta\,X_i\lambda_{1;i+1} + (\beta\,X_i - \varepsilon_2 v_i - \sigma + 1)\,\lambda_{2;i+1} + (\varepsilon_2 v_i + \sigma)\,\lambda_{3;i+1}$

$\lambda_{3,i} = \frac{\partial H_i}{\partial Z_i}$

$\lambda_{3,i} = \Psi_3 + \theta\,\lambda_{1;i+1} + (-\theta + 1)\,\lambda_{3;i+1}$

with transversality conditions

$\lambda_{1,T} = \Psi_1$, $\lambda_{2,T} = \Psi_2$ and $\lambda_{3,T} = -\Psi_3$,

To obtain the optimality conditions, we take the variation with respect to control (u_i^*, v_i^*) and set it equal to zero, that is

$$\frac{\partial H_i}{\partial u_i} = 0$$

$$\frac{\partial H_i}{\partial v_i} = 0$$

$$u_i = \frac{X_i\,(\lambda_{1;i+1} - \lambda_{3;i+1})\,\varepsilon_1}{\beta_1}$$

$$v_i = \frac{Y_i\,(\lambda_{2;i+1} - \lambda_{3;i+1})\,\varepsilon_2}{\beta_2}$$

□

4. Results and Discussion

4.1. Control of susceptible passengers. The figures below illustrate the results of our first strategy, which is to control susceptible passengers.

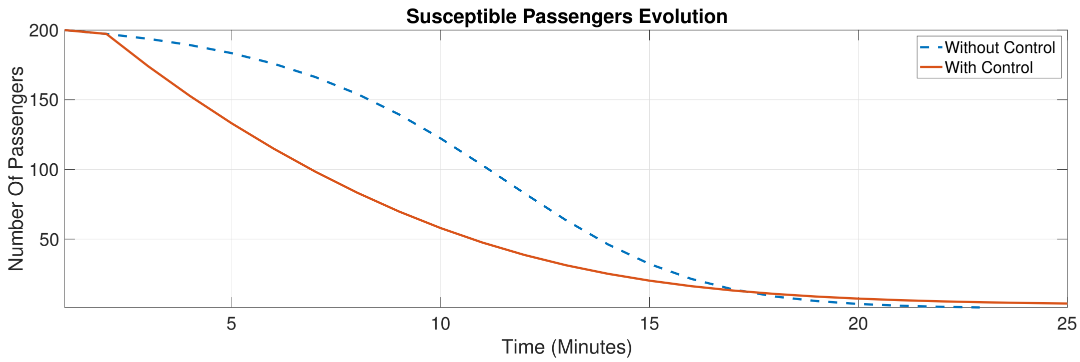

FIGURE 3

It can be seen that, due to the control, the number of passengers who are susceptible to panic decreases more quickly in the first fifteen minutes.

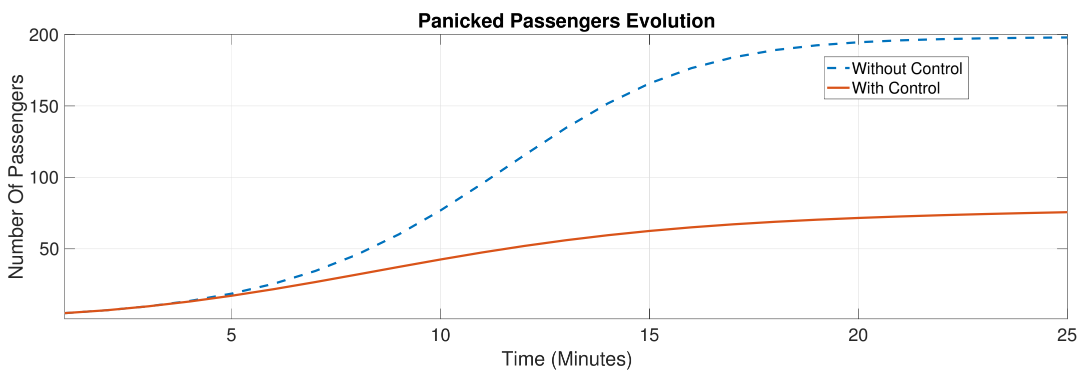

FIGURE 4

Controlling susceptible passengers decreases the amount of panicked passengers to less than 33% when compared to not controlling them.

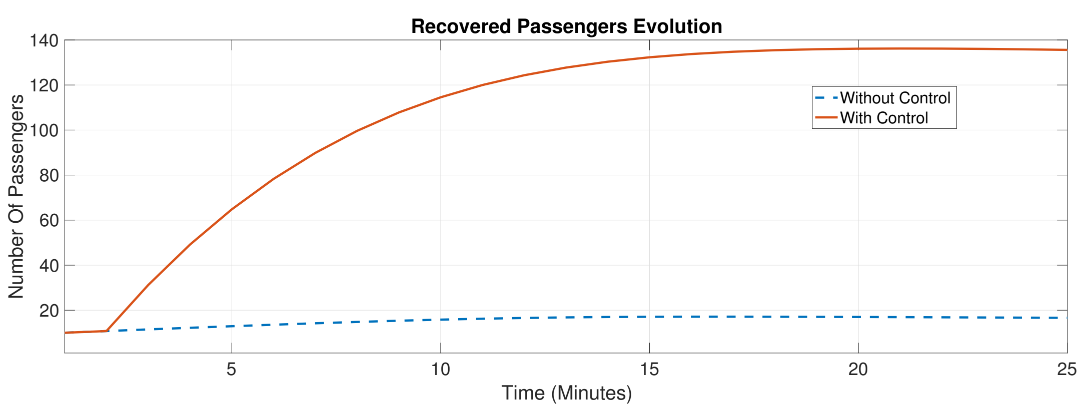

FIGURE 5

The number of passengers recovered has grown sevenfold as compared to the number without control, but still only represents about 70% of the total number of passengers on board the plane.

4.2. Control of Panicked passengers. The figures below illustrate the results of our second strategy, which is to control Panicked passengers.

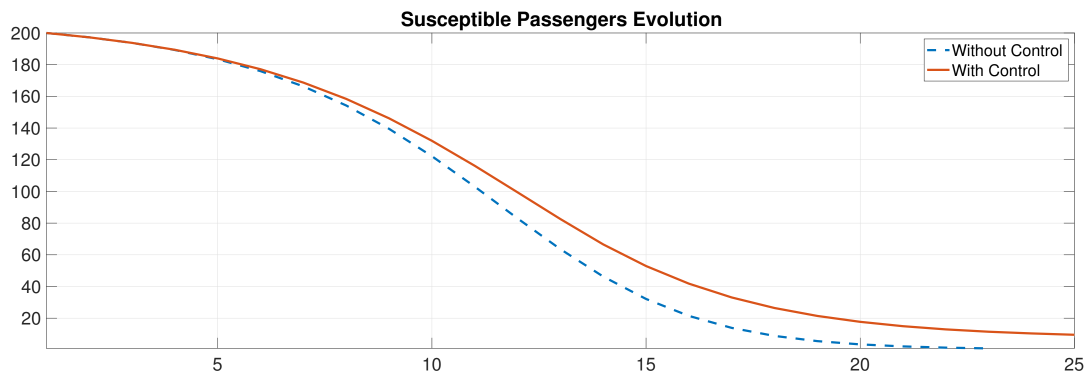

FIGURE 6

In contrary to the first strategy, control appears to delay the descent of susceptible passengers.

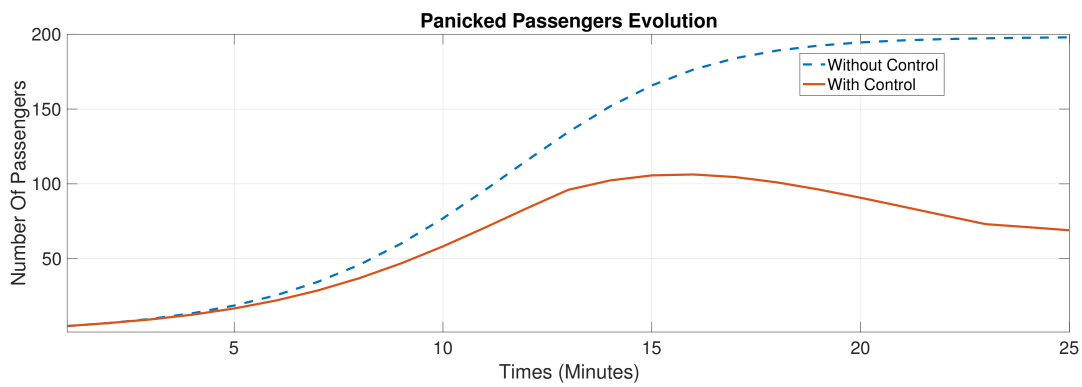

FIGURE 7

This strategy produces nearly the same results as the first, with the exception that in the 15th minute, the number of panicked passengers exceeds 100.

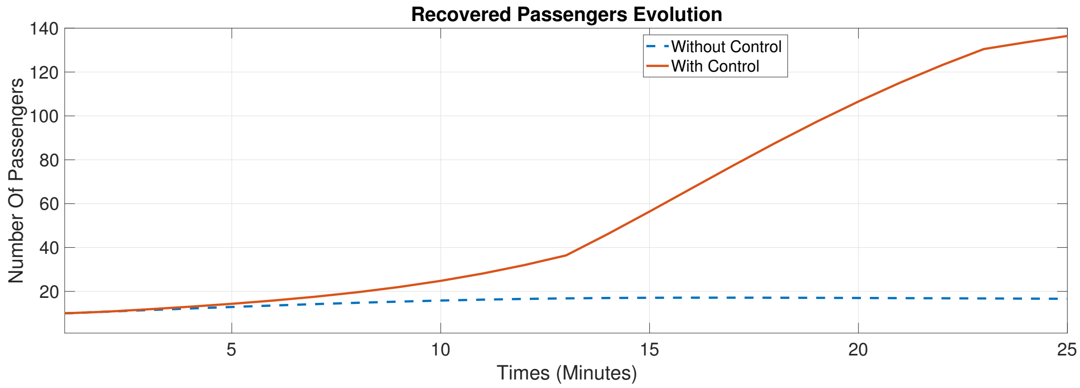

FIGURE 8

Recovered passenger's evolution grows slower than the first strategy.

4.3. Control of Susceptible and Panicked passengers. The evolution of the compartments by acting on the Susceptible passengers and Panicked.

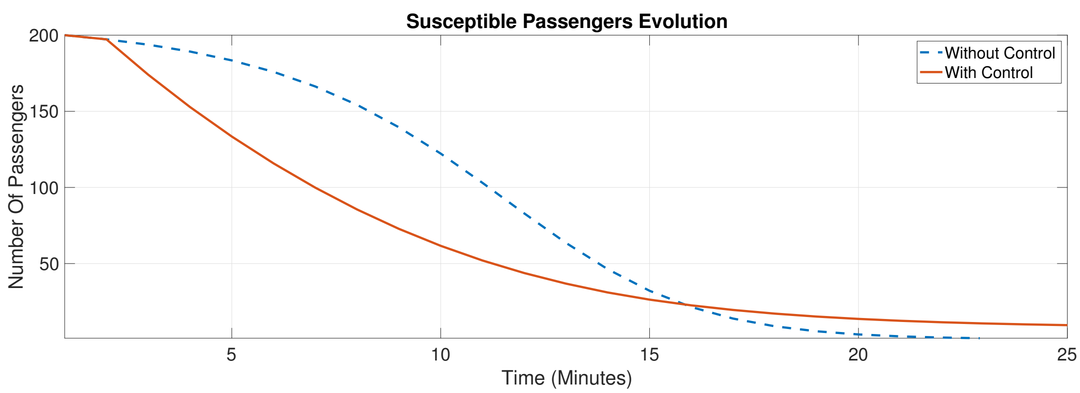

FIGURE 9

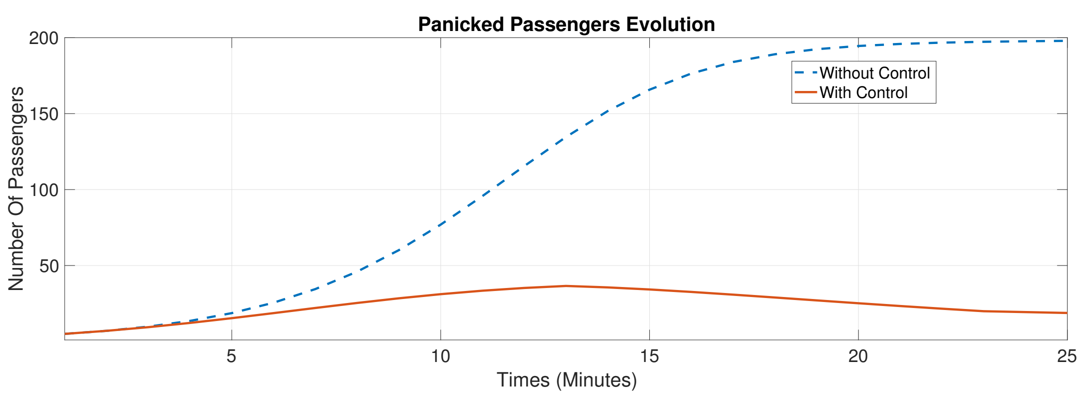

FIGURE 10

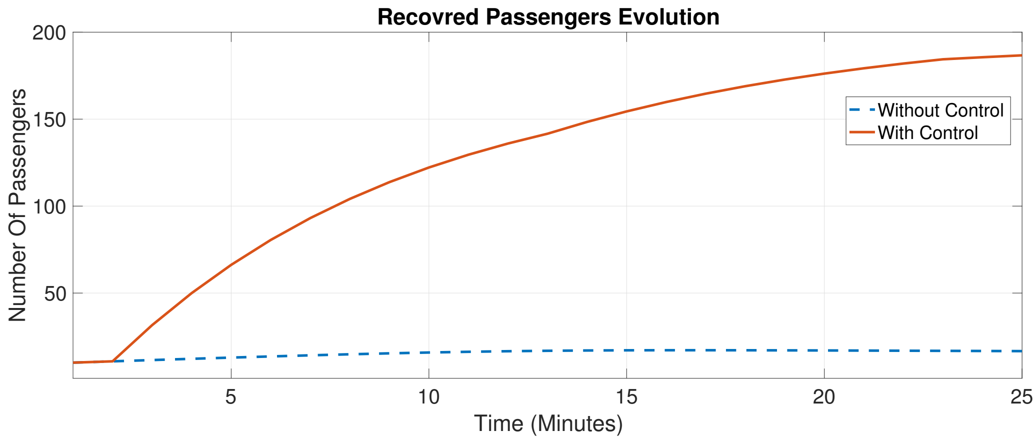

FIGURE 11

The use of both strategies limits the number of panicked passengers to less than 50 while increasing the number of people recovered.

5. CONCLUSION

This research looks at how panic spreads on an aeroplane during a trip using two distinct control strategies: the first focuses on susceptible passengers, and the second focuses on panicked passengers. The simulations conducted using Matlab reveal that combining both strategies is the most effective way to prevent panic from propagating across an aircraft.

CONFLICT OF INTERESTS

The author(s) declare that there is no conflict of interests.

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