Development of Hybrid Simulation Model of Air Traffic Management in the Terminal Control Area

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Abstract. The air traffic density at the Terminal Control Area can lead to several problems related to the safety and efficiency of flight operation if not adequately managed. These problems include the increased risk of crashes between aircraft, airborne and ground delays, waste of fuel and environmental problems caused by gas emission and noise. One of the analysis tools to solve these problems is the hybrid simulation model. The socio technic characteristics of the system can be observed more intact using a hybrid simulation model so that the results of the analysis more precise and comprehensive. This article describes the research framework and progress on the development of the hybrid simulation model of an ATM system in the Terminal Control Area. The final model will integrate of agent-based simulation, discrete event simulation, and system dynamics models. An agent-based simulation model that defines the movement of aircraft in the Terminal Control Area has been developed in this early research phase. The initial model can describe the rules for minimum separation between aircraft that are applied to ensure the safety of flight operations. The following aircraft will reduce its speed so that an adequate separation distance is obtained with the aircraft in front of it. The model then will be improved by integrating a discrete event simulation and system dynamics models on the initial model to obtain a complete hybrid simulation model.

1. Introduction

Passenger of world air transport has doubled every 15 years since 1977, and according to the International Civil Aviation Organization (ICAO), this growth continues [1]. Especially in the Asia Pacific region, the growth of air transportation in the past decade shows a high rate which is estimated to reach 37% of the world's air transportation market in 2017 from 33% in 2012 [2]. This is also supported by an increase in the addition of aircraft in the Asia Pacific region which will reach 37% in 2036 with the number of jet aircraft reaching 17,520 from the previous 6,830 in 2016 [3].

On the other hand, the growth brings its challenges, mainly resulting in air traffic congestion in the Terminal Control Area of several major hub airports. The higher density of flight traffic increases the risk of collisions between aircraft. Soekarno-Hatta International Airport (CGK), which is one of the busiest airports in the Asia Pacific, has experienced an increased risk of collisions and delays. This was conveyed by representatives of the Indonesian Air Traffic
Controllers Association (IATCA) [4] which stated that an increase in aircraft movements at CGK Terminals Control Area that were not matched by infrastructure availability resulted in prolonged delays and endangered flight safety.

The Terminal Control Area provides control on airspace around a large/busy airport; it has the highest level of Air Traffic Services including conflict detection services, separation determination, sequencing, and spacing. In the Terminal Control Area runs three flight operation scenarios at the same time they are arrival, departure and crossing flight [5]. The density of flight traffic at the Terminal Control Area can cause some problems in flight safety and operating efficiency if not properly controlled. These problems include increased risk of aircraft collisions, delays, waste of fuel and environmental disturbances caused by emissions and noise pollution.

In this research, a hybrid simulation model will be developed by integrating agent-based simulation, discrete event simulation, and system dynamics simulation models. Hybrid simulation modeling can better represent the characteristics of a complex system such as the ATM system [6]. The development of computational technology has also helped the reliability of this method in handling complex calculations which are a decrease of the complex phenomena of the modeled system. The hybrid simulation model will then be used to analyze the risk of collisions at CGK Terminal Control Area.

2. Research Methodology
2.1 ATM Hybrid Simulation

ATM systems have a large scale of problems as there are several human operators in the system (pilots, controller, and others) who each have the freedom to make decisions. By combining two simulation modeling methods, it is expected to reduce the limitations and improve the ability of the simulation method. Combining these two simulation coding methods is called hybrid simulation modeling [7].

The application of hybrid simulation modeling in the ATM research field is relatively recent. Wei and Li (2016) analyzed ATM systems from aspects of the internal operating mechanism and external behavior attributes [6]. In this research, the ATM hybrid simulation model was developed which was represented by the integration of DES and ABS. The ABS model is used to describe the micro-behavior of individual flight traffic and integrate the micro-behavior into dynamic macro performance at the system level. Agents included in the ABS simulation model include aircraft and flight traffic control personnel. The hybrid model is simulated on arrival and departure operations. Validation results show that the ATM hybrid simulation model has high accuracy regarding micro behavior and macro system performance.

The integration of DES models and SD models was carried out by Glover and Lygeros in 2004 in the form of an ATC model for the certainty of three-dimensional separation [8]. In this model, the aircraft is represented by a model of flight dynamics in the form of an airplane system dynamics model. DES model represents flight plans and logic variables in the Flight Management System (FMS). Then in 2016, Pasaoglu et al. developed the model by including the ATC model that was built with the paradigm of the DES model. The algorithm built has polynomial complexity related to the number of aircraft and waypoints [9].

2.2 System Description

The ATM system in the Terminal Control Area modeled in this research is limited to arrival operations only. The ideal arrival pattern of two-dimensional views in a Terminal Control Area serving two parallel runways is shown in Figure 1. The aircraft will enter the Terminal Control Area through one of four entry points, namely E1, E2, E3 or E4. The entry point is the transition points between en-route airspace and Terminal Control Area.

The determination of entry points coordinates in conventional systems is assisted by a system of land-based navigation aids such as Non-Directional Beacon (NDB), VHF Omni-directional Range (VOR) and Distance Measurement Equipment (DME). In a more advanced system using the Performance Based Navigation concept with R-NAV (Area Navigation) and RNP (Required Navigation Performance) systems, the positioning of these points is also assisted by satellite-
based navigation systems such as the Global Positioning System (GPS). At these checkpoints, it is also possible for aircraft to hold while waiting for its turn to enter the Terminal Control Area.

Aircraft entering the Terminal Control Area then fly towards runway by following certain trajectories defined with the help of navigation equipment, either land-based navigation equipment (NDB, VOR / DME) or satellite (GPS). The path is often referred to as Standard Terminal Arrival Routes (STAR). With guidance from Flight Management Computer (FMC) aircraft can easily fly along the track. In certain conditions, if needed, the aircraft ATC directives that contain the aircraft heading, height and also changes in speed or often referred to as vectoring.

Aircraft movements at Terminal Control Area at airports equipped with surveillance facilities such as Radio Detecting and Ranging (RADAR) will always be monitored by an air traffic controller. Through the assistance of RADAR, an air traffic controller will always keep the separation between aircraft to be maintained by the applicable separation procedures. For the arriving aircraft, the most commonly used separation is horizontal separation. While between departing and arriving aircraft usually vertical separation is utilized [10].

![Figure 1](image.png)

**Figure 1.** Ideal pattern of arrival in Terminals Control Area [11]

Terminal Control Area also applies speed restrictions to certain segments. The closer the runway is, the lower the speed limit. The trajectory segments will likely also meet at certain points which are often referred to as merging points. Terminal Control Area path will end at the runway’s entry gate where the final approach path begins. The final approach path and the runway generally are integrated into the runway system.

### 2.3 Modeling Concept

ATM system simulation modeling will apply the concept of a hybrid simulation model. The modeling concept that integrates ABS, DES and SD models is outlined in Figure 2.
2.3.1. **Agent-Based Simulation Model (ABS).** The ABS model is used to model the dynamics of decision making and interaction between agents who are representatives of air traffic controller, pilot and ATC system. Each agent is given the ability to make decisions and take action under different conditions to achieve its goals. Each agent also can interact with other agents. The human agent model (controller and pilot) used in the research is a human agent model developed by Bouarfa et al. (2013). The model has three main entities, consist of situation awareness, information processing, and cognitive control.

Situation awareness describes agent perceptions of influential elements, understanding of current conditions and future status projections [12]. Errors can occur in processing information because of the limited processing capacity of a human. Situational awareness and workload will affect the cognitive control mode, whether strategic, tactical, opportunistic or scrambled [13].

The ATC system model is a non-human agent that has a surveillance system, alerting system and communication system models [13]. The surveillance system model provides information on the estimated position and speed of the aircraft. This information is then used by the controller to guide traffic, especially to keep a safe separation between aircraft. The system will elicit an alerting if a critical situation occurs in the form of a reduced separation distance that is considered dangerous based on information from the monitoring system. The communication system model bridges the communication between the pilot and the air traffic controller. The ATC system has a system condition parameter in the form of varying levels of reliability and availability.

2.3.2. **Discrete Event Simulation Model (DES).** Flight plan modeling and Flight Management System (FMS) are represented using the DES model. Flight plan will determine the aircraft’s arrival time at a particular waypoint whereas the FMS functions as an aircraft control system responsible for generating inputs (u) based on the state variables (x), flight plan information and the action of the pilot who gets orders from ATC [9].

There are four discrete state variables in the FMS model, namely flight level (FL), way-point index (WP), acceleration mode (AM) and climb mode (CM). FL represents a renewed flight altitude based on $x_3$ conditions. FL is also used to determine the nominal speed ($V_{nom}$). WP represents the number of waypoints in the flight plan. AM shows whether the plane is increasing or reducing speed, or is flying at a constant speed. CM determines whether the aircraft is climbing or descending or leveling.
2.3.3. System Dynamics Simulation Model (SD). System dynamics simulation models are used to model aircraft dynamics. The aircraft model to be developed has three control inputs which consist of engine thrust \( u_1 \), turn angle \( u_2 \) and flight path angle \( u_3 \). Five state variables that build airplane models consisting of horizontal positions \( x_1 \) and \( x_2 \), altitude \( x_3 \), true airspeed \( x_4 \), heading angles \( x_5 \), and aircraft mass \( x_6 \). Wind velocity is also modeled, \( W = (w_1, w_2, w_3) \) which is a representation of disturbances from the environment \[8\].

\[
\begin{align*}
\dot{x}_1 &= x_4 \cos(x_5) \cos(u_3) + w_1 \\
\dot{x}_2 &= x_4 \sin(x_5) \cos(u_3) + w_2 \\
\dot{x}_3 &= x_4 \sin(u_3) + w_3 \\
\dot{x}_4 &= - \frac{C_D S \rho(x_3) x_4^2}{2x_6} - g \sin(u_3) \frac{u_1}{x_6} \\
\dot{x}_5 &= - \frac{C_L S \rho(x_3) x_4}{2x_6} \sin(u_2) \\
\dot{x}_6 &= - \eta u_1
\end{align*}
\]

\( C_L \) and \( C_D \) are lift and drag coefficient, \( S \) total surface area of the wing, \( \rho(x_3) \) air density and \( \eta \) is the thrust coefficient relative to fuel consumption.

2.3.4. Hybrid Simulation Model. After the three simulation models above have been successfully built, the three are integrated into a hybrid simulation model that can better represent the ATM system in the Terminal Control Area. The hybrid simulation model will be able to describe the air traffic dynamics in the ATM system that is represented by separation control between aircraft and aircraft dynamics controlled by FMS. Human factors are represented by the dynamics of human interaction (pilots and controllers) and humans with tools (pilots, controllers and ATC systems).

3. Results and Discussion

At the stage of developing the ABS model, each flow of aircraft arrival can be divided into several segments with a certain maximum speed. Each segment connects two waypoints. Each waypoint is a different agent. An aircraft that is also an agent will experience heading changes and speed when reaching a specific waypoint according to the RNAV STAR procedure that applies in that segment.

The system modeled in this study is the arrival operation at Soekarno-Hatta Airport. Development of ABS models using NetLogo. The elements in the model are defined as agents consisting of aircraft and waypoints. The aircraft has properties in the form of initial position, agent form, differentiating color, heading, and speed while waypoint has properties in the form of initial position, distinguishing color, shape, and position.

The aircraft moves to follow the STAR route through predetermined waypoints at a certain speed by the applicable speed limit. The aircraft is ordered to change the heading towards the next waypoint when it has been through a waypoint. The aircraft is also programmed in such a way that it can be precisely at the coordinates of a waypoint before changing the heading towards another waypoint. Also, the aircraft can maintain its separation from other aircraft by slowing or increasing its speed. When the simulation starts, the button on the interface will record the agent property in graphical form to determine the changes that occur throughout the simulation. The display of the simulation model is shown in Figure 3.
Figure 3. Display of Simulation Model of ATM System in Terminal Area

Longitudinal separation applies to the same track, reciprocal tracks and crossing tracks with separate provisions of 5 NM. The aircraft can detect other aircraft in front of it with a radius of 90° to the left and the right. The follower will reduce the speed with certain change factors if there is a conflict (the distance with the preceding aircraft is less than 5 NM) and a potential conflict warning sign will appear (red color).

The simulation model still has several limitations including the separation regulation strategy is only by making a speed reduction. The arrival of the aircraft can only be done at the same time; it cannot be arranged according to a specific schedule. The speed of the plane on a fixed route will only change if there is a potential conflict. Reduction of aircraft speed has not been made gradually.

The simulation model has been able to run well, even though it is still necessary to validate the model whether it has resembled the original system or not. The parameters that need to be observed are the terms of the separation between aircraft whether it has been fulfilled. The model also has not been able to accommodate the characteristics of the relationship between the pilot, controller and ATC system so that it is still necessary to improve the simulation model at the next research stage.

Additional data is also still needed regarding the guiding characteristics carried out by the controller, especially when facing critical situations. The interaction between humans and the ATC system also requires further exploration through in-depth interviews with the controller.

4. Conclusion

This article discusses the progress of research on developing a hybrid simulation model of an ATM system in the Terminal Control Area. Research has developed an agent-based ATM system simulation model at the Soekarno-Hatta Airport Area Terminal which is equipped with visualization of aircraft movements. Simulation model provided with visualization is an effective method for representing and analyzing complex systems such as ATM systems. However, validation of the simulation model is still needed to prove the simulation model developed can represent the ATM system accurately. The simulation model cannot be used to adequately reflect the characteristics of the ATM system in the Terminal Area because it does not include interactions between the pilot, controller and ATC system. Improvement of the simulation model is still needed to represent the socio-technic system better.
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