Using the system dynamics model on sustainable safety development of civil aviation

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Abstract: With the rapid expansion of flight services, civil aviation airports and air traffic controllers have long been operating at full load; the support capability cannot meet the actual development needs, which is placing increasing the pressure on safety considerations. Hence, in-depth studies on the dynamic relationships among support capability, safety and development and the timely adjustment of policies are imperative. A ‘growth and underinvestment’ model is used to construct a dynamic model of civil aviation sustainable safety development. Through the use of VENSIM software as a modelling tool and Tianjin as an example for simulation, the policy scenario for realising the sustainable safety development of civil aviation in this region is designed. Based on the simulation results, policy suggestions for the sustainable safety development of this region are proposed. It is also proven that the model can be applied to other fields.

Keywords: civil aviation; safety; support capability; sustainable development; system dynamics; causal analysis; china; air traffic control; model application; policy simulation.

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1 Introduction

At present, China's civil aviation industry is experiencing a flourishing period of rapid expansion. In 2017, China's civil aviation transport airports handled 1.148 billion passengers, an increase of 12.9% over the previous year, and 10.249 million flight takeoffs and landings, an increase of 10.9% over the previous year (Civil Aviation Administration of China, 2018a). There are 84 transport airports with an annual passenger throughput of more than 1 million (Civil Aviation Administration of China, 2018b).

With such rapid development, the civil aviation transport production system is struggling to meet the requirements for the normal and safe operation of flights. The congestion of airports and air traffic is becoming increasingly serious, and unsafe incidents occur frequently. During the 11 years from 2006 to 2017, the number of flight movements increased by 178%, with an average annual growth rate of 10.39%. However, the flight on-time rate showed an overall downward trend (Civil Aviation Administration of China, 2018c).

The increased congestion of airspace and airports not only greatly reduces transport efficiency and causes many delays but also brings great safety risks to civil aviation transportation. Flight delays and unsafe conditions in turn limit the ability to increase the number of flights. The government has taken measures to reduce development and increase capability. However, reduced development cannot meet the civil aviation market demand in China. Additionally, uncertainties regarding how, when, and by how much capability should be increased remain unresolved. Therefore, to achieve the safe, efficient and on-time operation of civil aviation, it is necessary to study the direct dynamic relationship among the support capability, safety and development of civil aviation to determine how to make policy decisions during the rapid development of civil aviation and to ensure the future sustainable and safe development of the overall civil aviation industry in China.

2 Literature review

Under the dual indicators of development and tolerance, development is limited by support capability, and safety risks ensue when development exceeds support capability. Initially, scholars studied civil aviation from a single development perspective. When studying the rise and fall of American People's Airlines, Morecroft (2008) found that the airlines lacked systematic thinking about development and quality and could not deal with the relationship between company development and quality pursuit, resulting in bankruptcy due to "growth and underinvestment". Later, from the combined perspective of safety and development, some scholars proposed that organisations should bear safety pressures corresponding to development pressures to achieve safety goals. During periods of rapid development in the industry, conflict between safety and rapid growth will appear (Cooke and Rohleder, 2006). However, in the conflicting relationship between rapid development and safety, the key factor of support capability cannot be ignored. Unsafe events will occur when support capability cannot keep up with the pace of development, and this lag will in turn constrain the development of the industry.

Therefore, to further analyse the relationship among civil aviation safety, capability and development and take into account the complex internal feedback relationship, previous studies have explored the mutual restraint between civil aviation safety support capability and sustainable development. In terms of the safety and development of air traffic control (ATC), scholars have analysed the dynamic feedback relationship among various system variables based on the safe operation process of ATC units and explored the optimal development mode of ATC units (Chen et al., 2014). However, the dynamic model does not take into account the number of controllers, amount of equipment and government supervision and approval of airspace, which have a strong impact on the safety operational capability of ATC units. The adjusted policy variables are safety input at the macrolevel and a flight approval coefficient. On the basis of the above studies, scholars have further refined the model with safety submodels (communications and navigation, control, information and meteorology), safety service submodels and airspace flow submodels and concluded that the greater the total safety investment is, the higher the controller's operational capability is (Chen, 2014). This study incorporates personnel and equipment considerations, but does not consider the impact of airspace management, and maintains policy adjustments from a macro perspective. In terms of the safety and development of airlines, scholars have found that an increase in safety investment can delay a decline in safety support levels (Zheng, 2014). However, the dynamic model does not consider factors such as pilots, dispatchers and maintenance personnel that are closely related to the development and safety of airline operations. In addition, scholars have studied the safety and development of airports by adjusting the proportion of safety and resource allocation investments (Wang et al., 2016). However, external environmental factors are not considered in the model construction. Factors such as GDP and population have a great impact on the demand for air passenger transportation, which in turn affects the development and safety of airports.

On the basis of research on the safety and development of airlines, airports and ATC subsystems, and considering that civil aviation is an extensive interlocking system, the Civil Aviation Administration should coordinate the safety of each subsystem when formulating various policies. Therefore, it is necessary to study the relationship among safety, capability and development from a holistic perspective. In addition, the abovementioned research on the sustainable safety development of each subsystem focused more on macroeconomic policy adjustments, such as adjusting the proportion of the safety investment, than on the adjustment of microeconomic factors (number of personnel, fleet size, etc.), resulting in limitations in the implementation of specific policies. Therefore, some scholars have more appropriately connected the airport safety support capability, ATC safety support capability and airline operational capability in the civil aviation safety and development system. In this paper, three policy scenarios are created by adjusting the number of flights and introducing a new airspace, additional aircraft, a new airport approval rate, a pilot promotion rate and a controller recruitment rate to obtain a model for the sustainable safety development of civil aviation that reduces the development level and increases the safety capability (Chen et al., 2017b). On the human side of the model, in addition to pilots and controllers, other personnel are equally important to airlines and airports. In addition, to scientifically study the sustainable safety development of civil aviation, it is necessary to observe not only the development trend of the safety situation but also the change trend of support flights and the flight regularity rate.

System dynamics is a successful causal analysis method that focuses on the dynamic process in integrated system thinking (Zhao et al., 2017) and can be used to simulate the impact of different policies on a system. Therefore, this paper, combined with the existing research and based on the system dynamics method, considers all the factors affecting safety and sustainable development in the overall industry and establishes a model for the sustainable safety development of the system dynamics of civil aviation through analysis of the dynamic feedback relationship between civil aviation subsystems and their internal factors. The model explores the sustainable development mode of China's civil aviation industry by simulating the future development status and safety status of the industry under specific civil aviation government policies.

3 Dynamic model of sustainable safety development for civil aviation

SD modelling can describe complex systems involving nonlinear relationships and make predictions based on computer simulations. VENSIM is a mature simulation platform that includes a visual modelling process, a simulation operation and an integrated function for outputting graphical results. In this paper, the SD method is used to determine a causal feedback relationship between the model elements followed by determining the observation variables and policy adjustment variables. VENSIM software is used to build a model and set the model parameters and equations, from which a model stock flow diagram is produced. Then, different scenarios are created to observe the variation trend of each variable for policy adjustment and to provide specific operational plans and visual simulation results for decision makers.

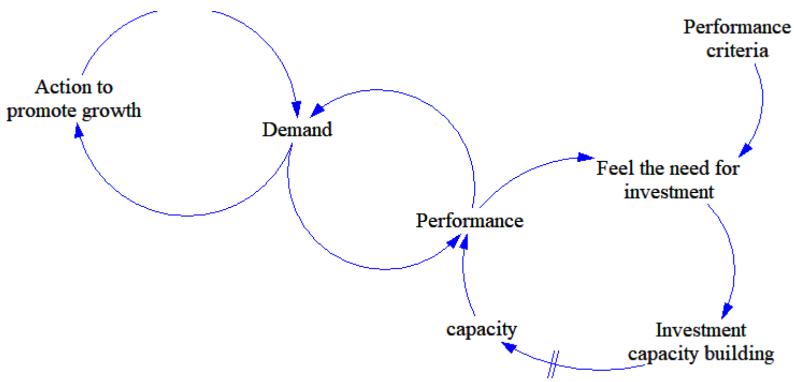
3.1 System analysis and concept model construction

The civil aviation industry is based on a transportation network with airports at the nodes. The ATC guarantees the formation and operation of this network. Airlines provide air transportation across the network, that is, the spatial displacement of passengers and goods (Chen, 2002). The civil aviation government is the industry supervision and management department that formulates policies according to the characteristics and relationships among the airports, the ATC and the airlines to enable the safe and efficient operation of the industry (Chen et al., 2017b). The system has three subsystems for airline capacity development, airport safety support and ATC safety support.

The civil aviation sustainable safety development system involves many internal structural elements/variables, among which a nonlinear feedback relationship exists. For example, market demand stimulates airlines to add new routes or flights along with the corresponding introduction of aircraft and pilots. When the number of pilots is insufficient to meet existing flight needs, that is, there is a low man-machine ratio, the workload of pilots and operational pressure increases, and ensuing fatigue can result in unsafe events. Flight delays from small operational redundancies cause the administration to reduce a company's routes or flights. The action process of the system is also subject to delays. For example, airlines that introduce new aircraft need to obtain governmental approval and make contracts with the manufacturer, and there is a delay between ordering aircraft and delivery.

Prof. Jay W. Forrester and his team proposed the 'growth and underinvestment' model (Peter, 2009), wherein investment is based on performance standards and increases capacity. However, the delay in the increase leads managers to believe that no investment is required. Subsequent insufficient investment limits performance and affects growth. The civil aviation sustainable safety development system is characterised by the system feedback rule of the 'growth and underinvestment' model, which is shown in Figure 1.

Figure 1 'Growth and underinvestment' model (see online version for colours)

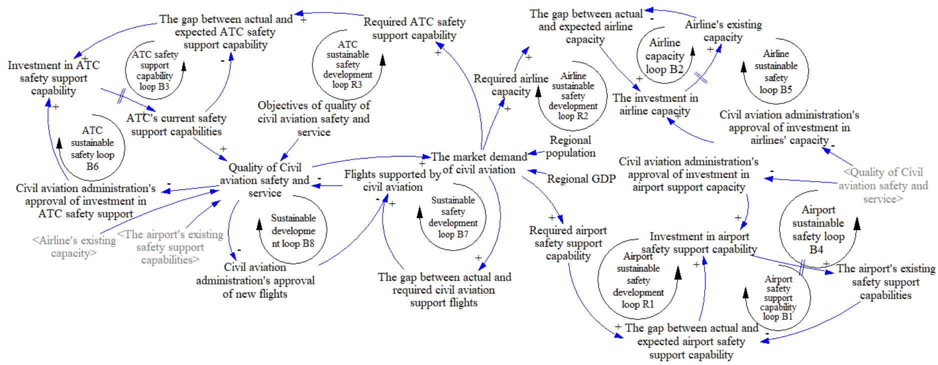


In this paper, the basic 'growth and underinvestment' model is used to analyse the relationship among the support units related to civil aviation transportation. Domestic and foreign research results are combined with real industry information to construct a conceptual model of continuous security development for civil aviation. 'Demand' refers mainly to that for development, service quality and security. 'Action to promote growth' refers to development (support flights). 'Performance' refers to the quality of safety services (as measured by the normality of available flights and the incident rate per 10,000 flights). 'Performance standards' are safety and quality objectives. 'Investment construction' refers to the input of safety support capability, and 'capacity capability' is the safety support capability. The conceptual model of sustainable safety development for civil aviation is shown in Figure 2. The factors in the figure are based on civil aviation reports, literature analysis and expert interviews.

3.2 Dynamic hypothesis and boundary selection

This paper mainly examines the functional relationship among civil aviation safety, capability and development, with capability including airport support capability, ATC support capability and airline operation capability. With safety as the leverage point, the supply-demand relationship between capability and development is determined. The boundary of the system is determined by making the following basic assumptions based on a system analysis and expert interviews.

Figure 2 Conceptual model of sustainable safety development of civil aviation (see online version for colours)



Assumption 1: Taking the unsafe event rate and the flight regularity rate under the usual air traffic conditions as the main line, consider the airline capability development subsystem, airport safety support subsystem and ATC safety support subsystem that reflect this line, including the system structure of personnel, equipment, management and flight support, unsafe event rate, and flight regularity rate in each subsystem.

Assumption 2: Variables such as safety objectives, flight regularity rate objectives, personnel introduction costs, equipment introduction costs, and equipment expansion costs enter the model in a constant form according to actual survey data. There is no change during the simulation period, and changes are made only during policy control simulation.

Assumption 3: The personnel factor considers only the supply and demand, resignation and retirement under normal working conditions. Facilities and equipment factors consider only the supply and demand, failure and scrapping under normal use. Weather as an environmental factor is relatively broad and uncontrollable, so at present, only the form of the external variables enters the model, and the specific value of the weather is determined by the experts.

Assumption 4: The expansion of the regional airspace is set to include not only scope expansion in a typical physical sense but also expansion after improving control procedures and controller capability and updating airport equipment and technology. The expansion of the airport includes not only scope expansion in the typical physical sense but also expansion after improving airport service procedures and updating the airport equipment technology.

Assumption 5: The objects of policy regulation that can be implemented are administrative, such as regional safety supervision or regional administration of civil aviation. The policy adjustment variables are determined only at the resource level that such administration can regulate, and the variables are input into the system by adjusting the program set to simulate the policy effect.

3.3 Causal loop diagram

The conceptual model is used to analyse the elements that characterise the safety support capability of each subsystem. The causal relationships for the civil aviation continuous safety development system are analysed using three feedback relationships (the safety support capability feedback loop, the sustainable development loop and the sustainable safety development feedback loop) in conjunction with literature data, research from websites related to civil aviation and expert interviews. A causal relationship diagram is constructed for each subsystem.

3.3.1 Causal analysis of airline capacity development subsystem

The factors that represent airline safety support capability include the number of professional personnel, such as pilots, dispatchers and maintenance personnel, and the number of aircraft.

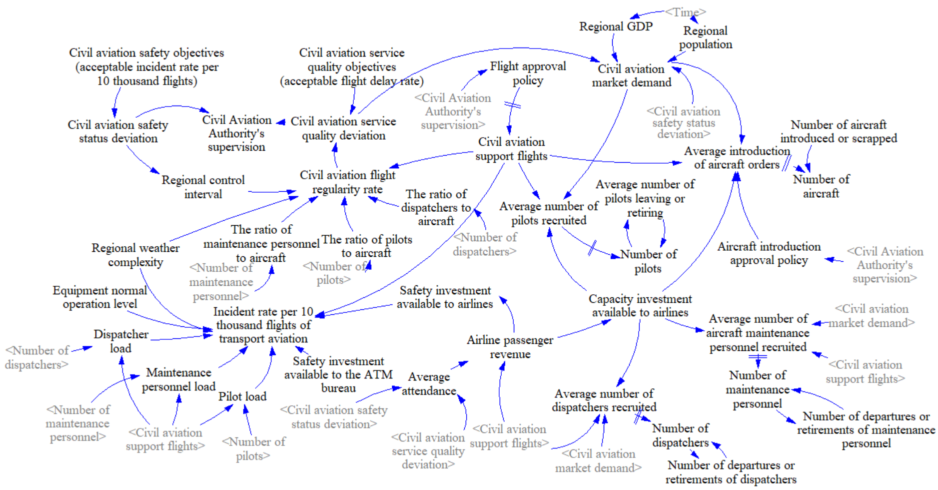
In the airline capacity feedback loop, there is a gap between the professional and technical personnel of each airline and the market demand. To meet flight demand, each airline introduces aircraft and recruits pilots, dispatchers and maintenance personnel. As aircraft provide air transport, their number largely represents the development scale of airlines (Pfaender et al., 2010), and the introduction of aircraft is controlled by government policy approval (Liehr et al., 2001). In a company's cost-benefit analysis, a high daily utilisation rate of aircraft will inevitably lead to a higher failure rate, thus affecting flight safety and normality. A flight cadet undergoes a long training period that incurs great expense, and a pilot must master complex system aviation knowledge (Chen et al., 2017a). With an increase in the number of flights, the demand for dispatchers also increases, and a large gap forms between the number of flights and the number of high-quality and sophisticated civil aviation maintenance personnel.

In the feedback loop of airline sustainable safety development, the greater the demand is, the more guaranteed flights and capacity are required. On the one hand, the more manpower and material resources are introduced, the higher the transportation capacity. On the other hand, to realise the demand for flights as soon as possible and to continuously increase the number of guaranteed flights, managers will pay less attention to safety, thus affecting safety and service quality and creating a vicious circle (Cooke, 2003). A statistical analysis shows that 15–20% of aviation accidents involving human factors are caused by pilot fatigue (Qiang et al., 2006; Steiner et al., 2012). When the number of pilots, dispatchers and maintenance personnel is insufficient, the greater the workload, the more operational errors occur, in turn affecting aviation safety.

In the feedback loop of sustainable development, economic development brings a greater demand for flights. Under the existing number of guaranteed flights, the relevant Civil Aviation Administration supervises and manages the airlines according to the objectives of flight regularity rate and safety. When safety and normality fail to meet the targets, measures will be taken to reduce flights and limit the introduction of additional aircraft.

The causality diagram that summarises the subsystem of airline capacity development is shown in Figure 3.

Figure 3 Causality diagram of airline capacity development subsystem (see online version for colours)



3.3.2 *Causal analysis of airport safety support subsystem*

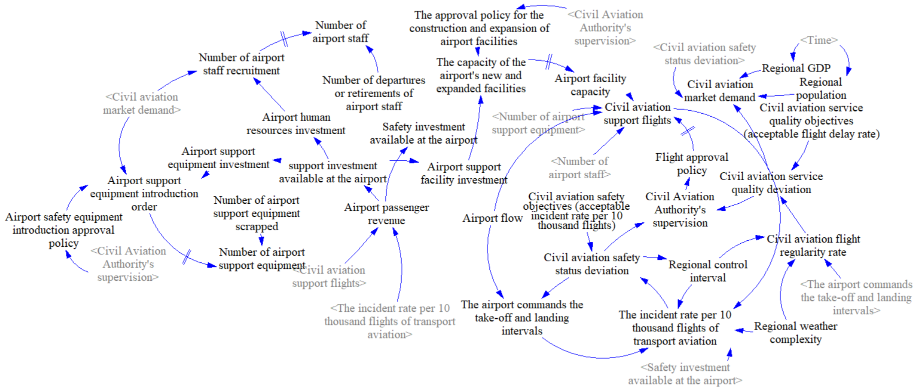
The factors representing airport safety support capability include the quantity of airport support equipment, the number of facilities, such as runways and aprons, and the intervals for aircraft takeoff and landing.

In the feedback loop of airport safety support capability, whether an aircraft can smoothly carry out various operations at the airport directly affects whether it can achieve an efficient connection between the air and the ground, which imposes high requirements on the support capability of the airport equipment (Li and Wang, 2013). Airport facilities refer to infrastructure, including runways, tarmac and terminals. The runway is a key part of the airport's capacity. Different airports have different numbers of runways, and the corresponding runway capacity therefore also differs. In addition, the higher the utilisation rate of the runway, the higher the operating efficiency is (Suryani et al., 2012). The higher the operating efficiency of the terminal control area is, the more flights can be managed in a given time, and the greater the airport capacity will be. Approach waiting or aircraft returns caused by airport programming or control factors will inevitably reduce the relative capacity of an airport.

In the feedback loop of airport sustainable safety development, factors such as service level, GDP and population affect the passenger demand for air transport. The greater the demand is, the more flights are scheduled each day, the more congested the airports are, and the higher the runway utilisation rate is (Li and Wang, 2013). To improve the current situation of airport congestion, it is necessary to expand airport capacity. The more flights that an airport guarantees, the higher the airport revenues are. These revenues affect safety investment and support capacity investment (Wang et al., 2016).

The causality diagram that summarises the airport safety support subsystem is shown in Figure 4.

Figure 4 Causality diagram of airport safety support subsystem (see online version for colours)



3.3.3 *Causal analysis of ATC safety support subsystem*

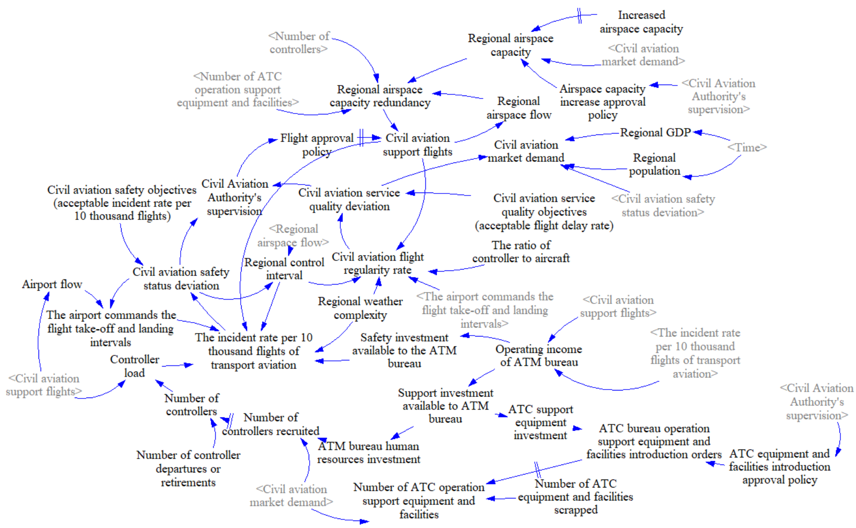
The factors representing the ATC safety support capability include the number of controllers, the quantity of control equipment and the airspace capacity.

In the ATC safety support feedback loop, although the ATC sub-bureaus have been increasing the recruitment of controllers, the number of mature controllers is in short supply compared to the growth rate of the number of airline flights (Chen et al., 2017b). The number of controllers does not match the development scale of current and future flights; in particular, the number of experienced controllers is seriously insufficient (Chen, 2014), and the speed of personnel training does not match the rate of the loss of personnel. The investigation reveals that some communication and navigation equipment is overdue for service or is malfunctioning. A problem with ATC equipment directly affects the controller's ability to monitor the aircraft and instruct the crew, thus affecting flight safety and normal operations. Increasing the number of ATC staff cannot solve the fundamental problem of air traffic congestion, which is related to flow management. Economic development has brought greater demand for flights, thereby increasing air traffic. When air traffic becomes saturated, the ATC burden increases, resulting in serious safety risks. To ensure safety, controllers increase the control intervals, leading to flight delays (Chen et al., 2014).

In the feedback loop of sustainable ATC safety development, economic development leads to greater demand for flights, thus increasing air traffic flow. In the situation of a large talent gap, the increased flow increases the controllers' burden, leading to a sharp increase in unsafe events caused by pressure and fatigue (Chen and Fan, 2017; Chen et al., 2014, 2017b). To ensure safety, controllers increase the control intervals and cause flight delays (Chen et al., 2014). Flight delays and unsafe events affect market demand. The income of ATC units comes mainly from the control route cost. The more support flights there are, the higher the route fee income and the greater the safety investment (Chen, 2014). To improve the safety level, the corresponding ATC safety investment increases. The higher the total safety investment is, the higher the control capacity and the safety level (Chen, 2014). The increased number of flights has crowded the airspace, such that expanded airspace capacity is required (Chen et al., 2017b).

The causality diagram that summarises the ATC safety assurance subsystem is shown in Figure 5.

Figure 5 Causality diagram of ATC safety support subsystem (see online version for colours)



3.4 *Stock and flow diagram*

3.4.1 *Policy adjustment variables and observation variables*

The policy regulatory variables can be divided into three main aspects: resource constraint, operation management and the external environment (Chen et al., 2014; Morecroft, 2008). The main resource-constrained variables are personnel, material and other aspects of investment, such as road maintenance budget (Fallah-Fini et al., 2010) and public transport construction investment (Armah et al., 2010). The main external environmental variables are the natural environment, economic environment and social environment, such as population and GDP. Operational management variables mainly refer to policies at the level of organisational supervision and management, including the service level, the safety level, the training intensity and the maintenance intensity, such as air ticket prices, the equipment maintenance quality level (Fallah-Fini et al., 2010) and the safety supervision level (Han et al., 2014).

Therefore, the main resource constraint variables of the dynamic model of civil aviation sustainable safety development are the input strength of personnel, equipment and facility construction. The main external environmental variables are the social and economic environment, policy supervision environment and the natural environment. The main operational management variables are policies at the level of organisational supervision and management, including airport flow management, airspace flow management, and safety management. In summary, policy adjustments are made from the perspectives of resource constraints, operational management, and the external environment. By observing the characterisation indicators of the different submodules, the influence law of the sustainable safety development system of civil aviation is obtained.

The policy adjustment variables and observation variables of the dynamic model of civil aviation sustainable safety development are summarised in Table 1.

Table 1 Summary of policy adjustment variables and observation variables

Type of influence factor	*Type of policy adjustment*	*Policy adjustment variable*	*Observation variable*
Resource constraint factor	Personnel	Number of controllers, number of pilots, number of maintenance personnel, number of dispatchers	Civil aviation support flights, civil aviation flight regularity rate, incident rate per 10,000 flights of transport aviation
	Equipment	Number of ATC operation support equipment and facilities, number of aircraft	
	Facility	Airport facility capacity, regional airspace capacity	
Operational managemen t factor	Airport traffic management	The airport commands the takeoff and landing intervals	
	Airspace flow management	Regional control interval	
	Safety management	Safety investment available to airlines, safety investment available to ATM bureau	
External environment al factors	Social economy	Regional GDP, regional population	
	Policy supervision	Flight approval policy, approval policy for the construction and expansion of airport facilities, airspace capacity increase approval policy, ATC equipment and facilities introduction approval policy, aircraft introduction approval policy	
	Natural environment	Regional weather complexity	

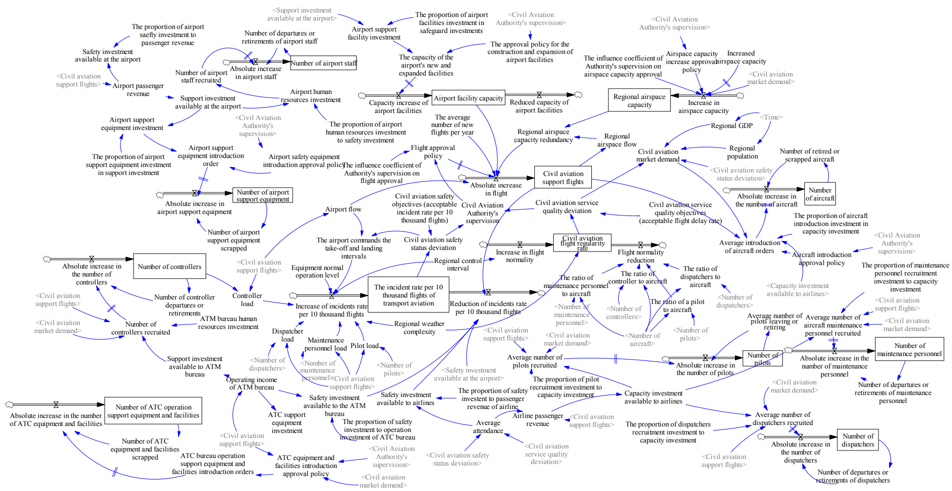
3.4.2 System dynamics model

The variables of the civil aviation flight regularity rate, the number of civil aviation support flights and the civil aviation market demand are taken as intermediate variables and combined with the relationship among the airlines, airports and ATC to determine the causal relationship of the three subsystems. Based on the causal feedback graph, the flow chart of the sustainable safety development of civil aviation is obtained through an analysis of the nature of each variable combined with the determination of the policy adjustment variables and observed variables, as shown in Figure 6.

4 Model application

Tianjin is used as an example for the application of the dynamic model of civil aviation sustainable safety development. Based on actual Tianjin civil aviation data, the model equations and parameters are determined, the model is tested and the basic simulation is carried out. According to the results of the simulation, policy scenarios of continuous safety development for Tianjin civil aviation are established. After the simulation, policy recommendations for the sustainable development of Tianjin civil aviation are proposed.

Figure 6 Civil aviation continuous safety development stock and flow diagram (see online version for colours)



4.1 *Model equations and parameters*

The model equation is determined according to the nature of each variable, and the quantitative relationship among the model variables is established by means of historical data or by consulting the literature and experts. The parameters of each variable are obtained and input to the VENSIM software, and the data processing function module in VENSIM is used to establish the model equation.

Three methods are used to determine the variable parameters in the model. First, data are collected from multiple sources, such as academic research, government reports and national statistical yearbooks or directly available data from the relevant websites of civil aviation in China. Second, the system dynamics characteristic function is used to determine the parameter value of each dependent variable; for example, the table function method is used to determine the population of Tianjin and the Tianjin regional GDP because it is difficult to determine the specific function expression between variables. Third, field data survey and data processing methods, such as expert interviews and scoring, are used. The coefficient is obtained by using the scoring formula, such as the relationship between the degree of complex weather in Tianjin and the increase in the incident rate per 10,000 flights.

The main variables of the system dynamics model are categorised into four groups: state variables, rate variables, auxiliary variables and constants. The first three types of variables are used to construct equations. The constant term is input as an initial value at the start of the simulation. The main equations in this paper are shown in Table 2.

Table 2 Equations for main variables used in model

Variable type	*Number*	*Variable name*	*Equation*	*Unit*
State variable	1	Number of Tianjin civil aviation support flights	INTEG (absolute increase in number of flights, initial value of support flights)	Flight
	2	Incident rate per 10,000 flights of Tianjin transport aviation	INTEG (increase in incident rate per 10,000 flights – reduction in incident rate per 10,000 flights, initial incident rate per 10,000 flights)	Dmnl
	3	Tianjin civil aviation flight regularity rate	INTEG (increase in flight normality – decrease in flight normality, initial value of flight normality)	Dmnl
Rate variable	4	Absolute increase in airport support equipment	INTEGER(DELAY1(airport support equipment introduction order, 0.25)-quantity of airport support equipment scrapped)	Set
	5	Increase in incident rate per 10,000 flights	0.6*0.3*pilot load + 0.6*0.2*dispatcher load + 0.6*0.2*maintenance load + 0.6*0.3*controller load + 0.15*regional weather complexity + 0.2* 0.4*ABS((regional control interval-0.25)/0.25) +0.2*0.6*ABS((airport commands take-off and landing intervals-0.25)/0.25)+0.05* equipment normal operation level	Dmnl
	6	Absolute increase in number of flights	DELAY1(IF THEN ELSE(flight approval policy *average number of new flights per year <= MIN(regional airspace capacity redundancy，airport flow)*365*20, 1)	Flight
Auxiliary variable	7	Number of retired or scrapped aircraft	Number of aircraft *0.033	Flight
	8	Supervision by Civil Aviation Authority	Civil aviation safety status deviation*0.6 + civil aviation service quality deviation *0.4+0.7	Dmnl
	9	Civil aviation market demand	IF THEN ELSE(civil aviation safety status deviation >=0.025:OR: civil aviation service quality deviation >=0.025，0.8*0.2256* (regional GDP*10000/regional population)^ 1.2078)	Flight

Dmnl denotes dimensionless units.

The state variables describe the accumulation of system variables over time. In the VENSIM software, the equation is described as: state variable = INTEG (inflow rate-outflow rate, initial state variable Value), where INTEG is the symbol for digital integration.

The rate variable reflects the rate of change of the cumulative rate, which is mainly determined by the increase and decrease in the accumulation of the state variable.

The following functions are used in VENSIM. DELAY1 is a material delay function: for example, 0.25 in the equation for the variable "absolute increase in airport support equipment" denotes that 0.25 years are required from booking to deployment for the airport support equipment. The INTEGER function is used for rounding.

IF THEN ELSE (condition, A, B) is a conditional function, that is, the respective variable takes the value of A when the specified condition is met and takes the value of B otherwise. For example, the equation for the variable "absolute increase in number of flights" represents the application, approval and operation of a new flight. The delay is one year. Thus, the number of additional approved flights cannot exceed the annual redundancy of the airport or airspace.

ABS is an absolute value function. For example, this function is used to take the absolute value of the equation of the variable "increase in incident rate per 10,000 flights". Incident statistics show that among the factors affecting unsafe incidents, personnel account for 60% (pilots: 30%; controllers: 30%; dispatchers: 20% and maintenance personnel: 20%), weather accounts for 15%, management accounts for 20% (control interval: 40% and take-off and landing interval: 60%), and equipment accounts for 5%. Based on interviews with staff, the regional control interval is 0.25 hours/sorties, and the take-off and landing interval determined by airport commands is 0 .25 hours/sorties. This analysis is used to obtain the parameter values of the equation for the aforementioned variable.

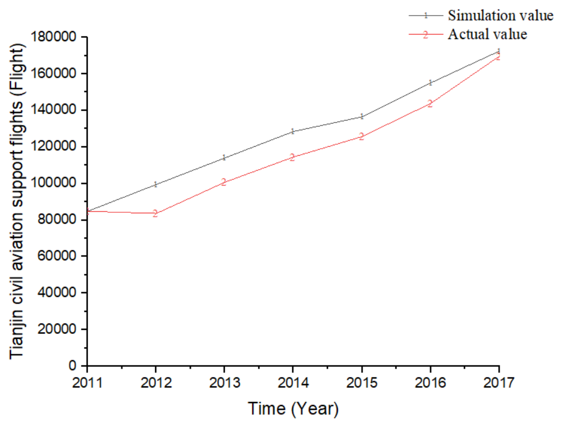
Auxiliary variables are intermediate variables in the feedback relationship that are indispensable for creating connections in the system. We consider the equation for the variable "number of retired or scrapped aircraft". Under normal circumstances, the service life of an aircraft is approximately 25–30 years, such that the number of retired and scrapped aircraft accounts for 3.3% of the total number of aircraft. Considering the speed at which an airline scraps or decommissions an aircraft after 30 years, the aircraft is infinitely quantified, and 1/30 of an aircraft is scrapped each year. For the equation for the variable "supervision by Civil Aviation Authority", interviews with bureau experts were used to calculate influence coefficients for the deviation in the safety status and the deviation in the service quality of 0.6 and 0.4, respectively.

The initial values of the state values and constants in the model are statistically analysed using the three parameter determination methods described in the second paragraph of 4.1.

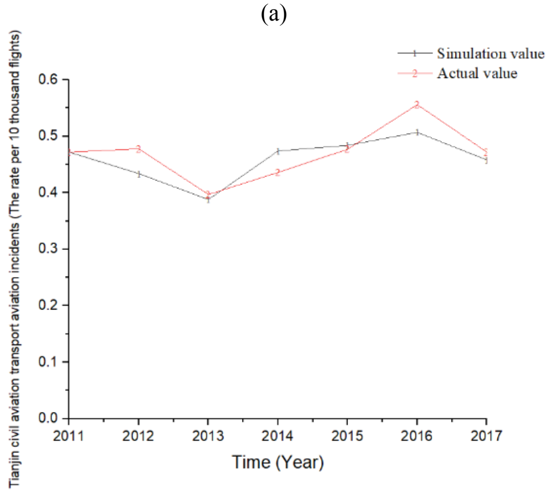
4.2 Model validation

A dimensional consistency test, structural test and behaviour recurrence test were used to test the dynamic model of Tianjin civil aviation sustainable safety development. The 'Units Check' function in VENSIM indicated that the model passed the dimensional consistency test, and the 'Check Model' function in VENSIM indicated that the model passed the structural test. The behaviour recurrence test based on the data for the national 12th five-year period from 2011 to 2017 was used with a step size of unity and a unit of a year. The initial value of 2011 was input into the model, and the 'Simulate' function was implemented to compare and analyse the real and simulated data from 2011 to 2017. The resulting behaviour consistency test curve is shown in Figure 7. The error range of the model is within 5% ~15% (Sterman, 1987), which is reasonable and shows that the model passes the behaviour consistency test.

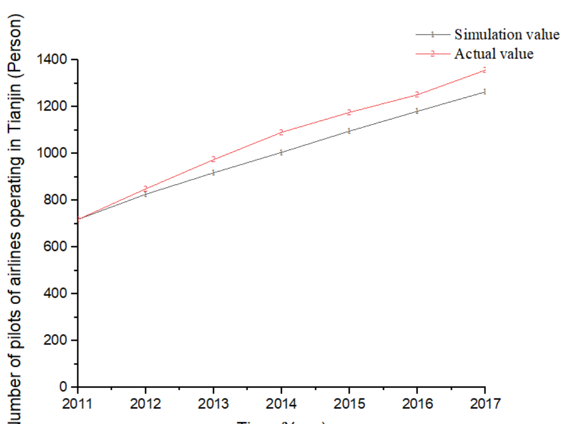
Figure 7 Behaviour consistency verification curve: (a) number of Tianjin civil aviation support flights; (b) incident rate per 10,000 flights of Tianjin transport aviation and (c) number of pilots (see online version for colours)



(a)



(b)



(c)

5 Scenario simulation

5.1 Basic simulation

No variables were adjusted, and the actual data for Tianjin Civil Aviation in 2016 were used as the initial input to the VENSIM software simulation. Based on the 13th five-year and 14th five-year plans of civil aviation in China, the simulation starts in 2016 and stops in 2025. The step length is 1, and the unit is year. The change trend of each variable from 2016 to 2025 predicts the development trend of Tianjin civil aviation safety if no new measures are taken, providing the basis for the subsequent formulation of the adjustment plan.

The actual data of each variable in 2016 are input into the model, and the simulation is carried out using VENSIM software to obtain the trend of support flights, flight regularity rate and incident rate per 10,000 flights in 2016–2025, as shown in Figure 8.

Figure 8 Basic simulation results: (a) number of Tianjin civil aviation support flights; (b) Tianjin civil aviation flight regularity rate and (c) incident rate per 10,000 flights of Tianjin transport aviation

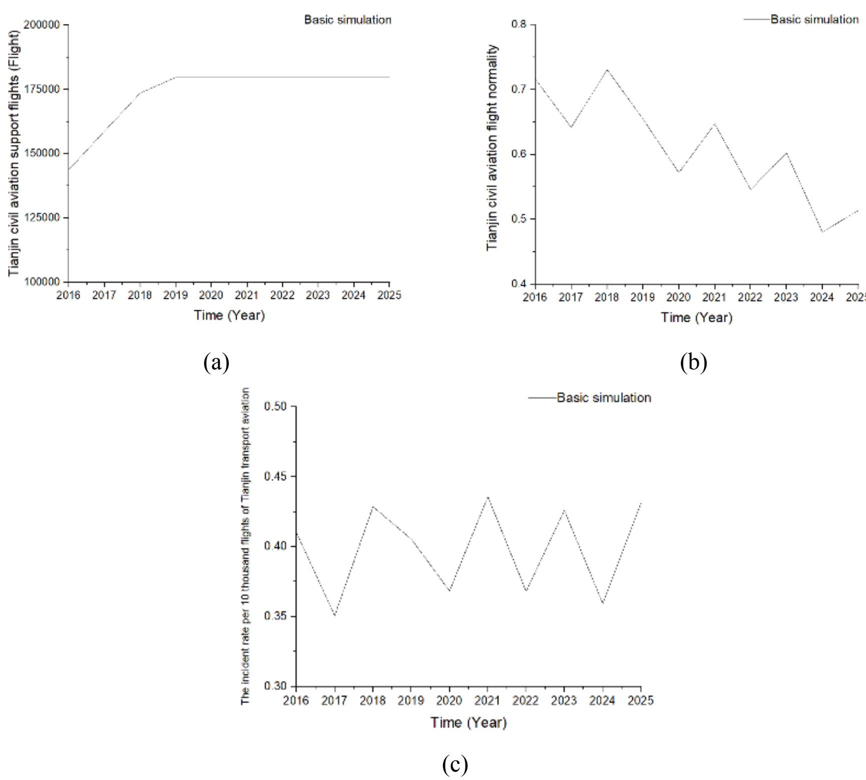


Figure 8(a) shows that at the current resource investment and support capacity levels of Tianjin civil aviation, the number of support flights in 2016–2019 increases rapidly, but from 2019–2025, the number of support flights maintains a slow increase and then tends to become flat. As far as the current support capacity is concerned, the number of support flights reaches saturation and cannot be increased further.

Figure 8(b) shows that with the current development and support capacity of Tianjin civil aviation, the flight regularity rate shows a declining fluctuation until 2025, at which time the flight regularity rate drops to 0.514, which is 28% lower than that in 2016 and far short of the flight normality target (>=0.8).

Figure 8(c) shows that with the existing development and support capabilities of Tianjin civil aviation, the incident rate per 10,000 flights of Tianjin transportation aviation incidents experiences nonperiodic fluctuations in 2016–2025. The incident rate per 10,000 flights in 2025 is approximately 0.431, which does not meet the safety target (<=0.4 million times).

In summary, maintaining the current resource investment and support capacity of Tianjin civil aviation cannot achieve the goal of sustainable and safe development for the 10 years from 2016 to 2025, regardless of the number of support flights, the flight regularity rate or the incident rate per 10,000 flights. The conflicts between the supply and demand of capacity and development and between development and safety constantly emerge. Therefore, to ensure the safe and normal operation of Tianjin civil aviation in 2016–2025 and to increase the number of support flights for sustainable development, it is necessary to formulate a plan and take corresponding intervention measures.

5.2 Scenario analysis

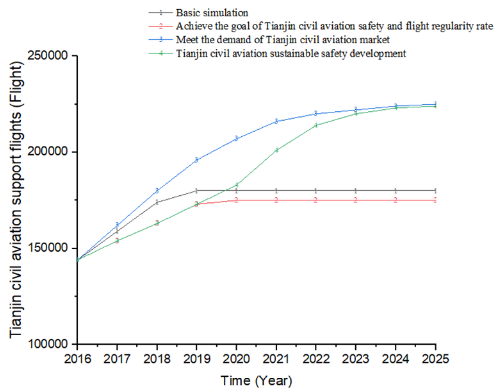
In response to the basic simulation results, to solve the capacity, safety, and development difficulties faced by Tianjin civil aviation, the policy scenarios for achieving the sustainable safety development of Tianjin civil aviation are established under the existing circumstances. The specific adjustment and comparison scheme are shown in Table 3.

Table 3 Policy adjustment plan for sustainable safety development of Tianjin civil aviation

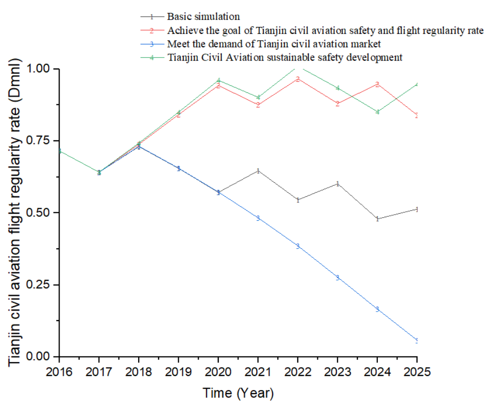
Program name	*Specific operation plan*
Basic simulation	For the case of no adjustment of variables, actual Tianjin civil aviation data from 2016 are used as the initial value input to model
Meet the demand of Tianjin civil aviation market	Relax the flight approval policy, increase the average number of new flights per year, and expand the Tianjin airport and ATC
Achieve goals of Tianjin civil aviation safety and flight regularity rate	Strictly apply the flight approval policy, reduce the number of approvals of new flights, and increase the input of professional and technical personnel, air equipment management, equipment investment, aircraft investment, airport safety investment, air traffic management safety investment and airline safety investment
Tianjin civil aviation sustainable safety development	2016–2019: Strictly apply the flight approval policy, reduce the number of approvals of new flights, expand the airport and ATC, and increase professional and technical personnel investment, support equipment investment for ATC branches, aircraft investment, airport safety investment, ATC branch safety investment and airline safety investment
	2020–2025: Maintain the expansion of the airport and air traffic control and the input intensity. According to the plan to "meet the demand of Tianjin civil aviation market," relax the approval policy for new flights and increase the number of new flights per year

The above scheme is input into the model for simulation, and the resulting variation trends of variables such as the number of Tianjin civil aviation support flights, the flight regularity rate and the incident rate per 10,000 flights are shown in Figure 9.

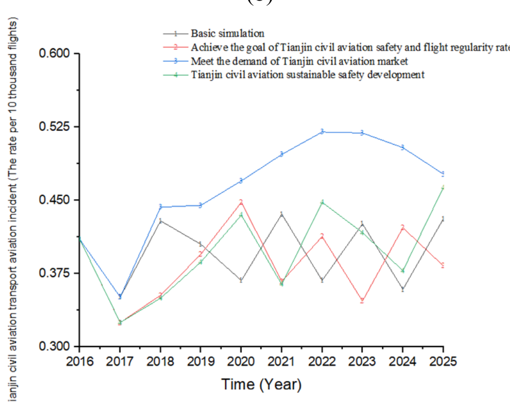
Figure 9 Simulation results for sustainable safety development: (a) number of Tianjin civil aviation support flights; (b) Tianjin civil aviation flight regularity rate and (c) incident rate per 10,000 flights of Tianjin transport aviation (see online version for colours)



(a)



(b)



(c)

As shown in Figure 9(a), in 2016–2019, the policy plan “Tianjin civil aviation sustainable safety development” and the policy plan “Achieve the goal of Tianjin civil aviation safety and flight regularity rate” follow the same trends. However, after 2019, the number of support flights under the policy plan “Tianjin civil aviation sustainable safety development” increases sharply and reaches 224,000 by 2025, which is only 1,000 fewer than that under the policy plan “Meet the demand of Tianjin civil aviation market”, with an annual average growth rate of 5.57%, meeting the development target for Tianjin civil aviation (annual average growth rate of 5%).

As shown in Figure 9(b), in 2016–2022, the policy plan “Tianjin civil aviation sustainable safety development” and the policy plan “Achieve the goal of Tianjin civil aviation safety and flight regularity rate” are more consistent, and the target Tianjin civil aviation flight regularity rate can be achieved. In 2023–2025, although there is a small fluctuation, the flight regularity rate drops to 0.85 in 2024 but remains above the target flight regularity rate.

Figure 9(c) shows that from 2016 to 2018, the change trend of the policy plan “Tianjin civil aviation sustainable safety development” is relatively consistent with that of the policy plan “Achieve the goal of Tianjin civil aviation safety and flight regularity rate.” In particular, in 2017, the incident rate per 10,000 flights is reduced to 0.325. In 2019–2021, the intervention effect of the policy plan “Tianjin civil aviation sustainable safety development” is relatively good, and the fluctuation remains at approximately 0.4. However, in 2022–2025, due to the increasing number of flights, the intervention effect is not as good as that of the plan “Achieve the goal of Tianjin civil aviation safety and flight regularity rate.”

Based on the comprehensive analysis of the support flights, the flight regularity rate and the incident rate per 10,000 flights, the policy plan “Tianjin civil aviation sustainable safety development” combines the advantages of “Meet the demand of Tianjin civil aviation market” and “Achieve the goal of Tianjin civil aviation safety and flight regularity rate.” Based on the premise of realising the safety and regularity goals of Tianjin civil aviation, the support flights can meet the needs of the national economy and meet the development goals.

5.3 Discussion

The best policy plan for the sustainable development of Tianjin civil aviation is as follows: in 2016–2019, strictly control the flight approval policy, reduce the number of new approvals for flights to 78% of the original estimate, and implement the expansion of Tianjin airport and ATC to increase the airport capacity to 48 flights per hour and the airspace capacity to 31 flights per hour in 2025. In addition, increase investment by 10–15% in professional and technical personnel, airport and ATC sub-bureau support equipment, aircraft, airport safety, and ATC sub-bureau and airline safety. From 2020 to 2025, maintain the expansion of airports and ATC, maintain various investment efforts, relax the approval policy for new flights, and increase the average number of new flights per year to 1.5 times that of 2016. Under this plan, the number of flights will gradually increase over time, the air transport incident rate will remain at a low level, and the flight delay rate will remain basically stable; thus, the development model is benign and sustainable.

6 Conclusion

In this paper, a dynamic model of civil aviation sustainable safety development is constructed based on the 'growth and underinvestment' model and three submodels for airline capacity development, airport safety support and ATC safety support. A relationship among the civil aviation support capability, development and flight regularity is thus obtained, and verifying the rationale and scientific basis of the model are verified.

This paper uses the real data of Tianjin civil aviation to analyse the trend of safety development that maintains the status quo of Tianjin civil aviation. According to the situation analysis results, Tianjin civil aviation cannot achieve the sustainable safety development goal of 2016–2025. The conflicts between the supply and demand of capacity and development and between development and safety are constantly emerging.

Therefore, policy scenarios for the sustainable and safe development of Tianjin civil aviation are established. According to the simulation results, the following policy recommendations for the sustainable and safe development of Tianjin civil aviation are proposed: in 2016–2019, strictly apply the flight approval policy, reduce the number of approvals for new flights, expand the airport and ATC, and increase investment by 10–15% in professional and technical personnel, equipment and safety. From 2020 to 2025, maintain the expansion of the airport and ATC and the input intensity and relax the approval policy for new flights.

The dynamic model of civil aviation sustainable safety development established in this paper is simulated with Tianjin as an example, showing that the model can be extended to other fields. The model can be adjusted to focus on a single policy, or multiple policies can be combined and adjusted. In addition, in future research, to further reduce errors in the operational results, the initial values and parameters of the model can be updated according to the actual situation.

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