Research on the efficiency of Beijing-Tianjin-Hebei airport group based on system dynamics

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Abstract. The Beijing-Tianjin-Hebei Airport Group is a nonlinear complex system with dynamic changes and feedback mechanisms. It is difficult for a general model to simulate an airport group. This paper adopts the system dynamics method to establish the airport group efficiency evaluation model, adjust the variable parameters, and verify the policies implemented in each airport in this airport group. The study found that the overall efficiency of the Beijing-Tianjin-Hebei Airport Group has increased year by year. However, the Beijing Capital International Airport has experienced over-utilization of resources in the past three years. The efficiency of Tianjin Binhai International Airport has been rising, changing from the excessive resource redundancy in 2010 to the nearly full use of airport resources in 2017. Although the efficiency of Shijiazhuang Zhengding Airport has increased, the airport resources have been still wasteful. Through the simulation of the airport group, we can understand the efficiency of the airport group and each airport, and fully understand the integrity of the airport group and the mutual impact mechanism between the airports.

1. Introduction
In 2017, a notice was issued, proposing to accelerate the coordinated development of civil aviation in Beijing, Tianjin, Hebei, and strive to build a world-class aviation airport group. The Beijing-Tianjin-Hebei airport group currently has nine airports, including Beijing Capital International Airport (PEK), Tianjin Binhai International Airport (TSN) and six airports in Hebei province including Shijiazhuang Zhengding International Airport (SJW). In 2017, the ratio of the passenger throughput of each airport in this airport group is shown in Figure 1. This airport group presents a single-level agglomeration of PEK. The passenger demand concentrated in PEK leads to a shortage of flights, exceeding the capacity the airport can guarantee, causing flight delays. TSN and SJW have less air transportation demand and airport resources are idle. The oversaturation of PEK and the redundancy of the other two airports have affected the overall development of the airport group. Therefore, research on the overall efficiency of airport groups and airport development policies is urgently needed.

At present, there are many research methods for efficiency, including Data Envelopment Analysis (DEA). DEA is very mature in the evaluation of airport efficiency, and can evaluate the efficiency of multi-input and multi-output, which is not affected by the data units, but is susceptible to extreme
values and random disturbances. Fernandes, Mustafa Lsa Dogan, He Yan, Jia Pinrong [1][4] studied the operational efficiency of airports using different models of DEA. Currently the study of airport group efficiency is little. Zhang Weina [5] used DEA to evaluate the coordination efficiency between the two airports. It evaluated the correlation between the input of one airport and the output of another airport, but did not reflect the characteristics of the airport group.

The airport group is composed of airport individuals that distinguish each other and interact with each other and work together on the development of the airport group. It is a complex system under the combined effect of the factors including regional economy, population, policies, airports, other airport groups and so on. The impact of regional economy, passenger demand, resource supply, etc. on the airport group is systematic. The development of the regional economy has a positive impact on the overall passenger demand of the airport group. When selecting an airport, passengers who choose an airport in the airport group may not choose another airport. To avoid homogenization when airlines establish bases or develop routes, only one airport within the airport group will be selected. Therefore, the airport group emphasizes the common development of the individual and the overall.

System dynamics (SD) is precisely a method that emphasizes the combination of macro and micro, and studies the external influence and internal structure of the system. It can deal with complex system problems and can carry out policy simulation and predict policy effects. At present, there is no study of the airport group efficiency with SD, but the method has certain applications in the civil aviation field. Chen Yaqing [6] established a model for air traffic forecasting. Ioanna E. Manataki [7] assessed the performance of the Athens International Airport under different needs and resource allocations. In addition, there are many achievements in the study of urban transportation complex system using SD. Among them, the more famous researches are the urban dynamics model of Professor Forrester [8] and the travel generation model of Professor Shirazian. Hossein Haghshenas, Shiyong Liu, Xu Tianyou, and Yang Haoxiong [9][12] also used SD to establish urban traffic models, study urban traffic development, manage traffic congestion, and propose development policies.

Compared with the data envelopment method, the use of SD to study the efficiency of the airport group can not only better reflect the systematic, dynamics and complexity of the airport group, but also reflect the characteristics of the airport group, and simulate the impact and external influences between airports in the airport group. Therefore, based on SD, this paper analyses the dynamic structure and feedback mechanism of the airport group, and uses the Beijing-Tianjin-Hebei airport group as the research object to construct the Beijing-Tianjin-Hebei airport group efficiency model. Then this paper uses Vensim software to simulate and analyses the simulation results, and verifies the impact of the policies adopted by the airports on the airport group and other airports in this group.

2. Model building

2.1. Model hypothesis

Hypothesis 1: The passengers of Beijing-Tianjin-Hebei airport group are mainly concentrated in PEK, TSN, SJW. So this article assumes that this airport group consists of these three airports, and the other six airports are temporarily not considered.

Hypothesis 2: In general, airport efficiency is used to measure the extent to which resources are used. Therefore, it is assumed in this paper that the efficiency of each airport is the ratio of passenger throughput per airport to the capacity of each airport terminal. If the efficiency value is 1, the airport has the best allocation of resources and the highest efficiency. If the efficiency value is less than 1, the airport resources are not fully used and the airport efficiency is not high. If the efficiency value is greater than 1, meaning the excessive use of resources in the airport which can lead to congestion and declining service levels, so airport efficiency is not high too.

Hypothesis 3: The impact of each airport in the group is different, so the airport group efficiency is assumed to be the weighted average of the airport efficiency, and the weight is the ratio of the passenger throughput per airport to the total passenger throughput.
2.2. Variable meaning

Table 1. Model variables and meaning.

| Variable name | Meaning                                      | Variable name | Meaning                                      |
|---------------|----------------------------------------------|---------------|----------------------------------------------|
| GDP           | Regional GDP                                 | TLCC          | Low-cost base carriers of SJW                |
| AGDP          | Regional per capita GDP                      | TBSP          | Branch shipping points of SJW                |
| RP            | Regional permanent resident population       | FE            | Efficiency of PEK                            |
| TSPPV         | Regional transportation storage postal production value | SE            | Efficiency of TSN                            |
| RTP           | Regional total passenger throughput           | TE            | Efficiency of SJW                            |
| AFP           | Passenger throughput of PEK                  | FC            | Capacity of PEK                              |
| AFPI          | Passenger throughput increment of PEK        | SC            | Capacity of TSN                              |
| ASP           | Passenger throughput of TSN                  | TC            | Capacity of SJW                              |
| ASPI          | Passenger throughput increment of TSN        | FW            | Efficiency Weight of PEK                    |
| ATP           | Passenger throughput of SJW                  | SW            | Efficiency Weight of TSN                    |
| ATPI          | Passenger throughpout increment of SJW       | TW            | Efficiency Weight of SJW                    |
| FIPR          | International passenger ratio of PEK         | E             | Total efficiency of the airport group        |
| SBSP          | Branch shipping points of TSN                |               |                                              |

2.3. Causality diagram, feedback loop

The causal diagram can make complex problems simple and systematic, and provide scientific and clear ideas for analysing problems. After preliminary analysis, the system dynamics model of the Beijing-Tianjin-Hebei airport group proposed in this paper mainly includes three subsystems: PEK, TSN and SJW. The causal relationship diagram of the airport group is shown in Figure 2. The passenger throughput of three airports constitutes the total passenger throughput in this airport group, and the regional passenger throughput affects the productive value of the transportation, storage and post in the region, which in turn affects the regional overall GDP. The three airport subsystems are linked by economic factors to form the entire system of the airport group. There are three loops in the system dynamics model of this paper, as shown in Figure 3, reflecting the relationship between airport...
passenger throughput and economy. The increase in regional GDP leads to an increase in per capita GDP. The rise in per capita GDP stimulates people's travel needs, including air travel demand. As a result, the increase of the passenger throughput at PEK, TSN and SJW can bring the growth of airport benefit. The airport benefit can drive the development of the local economy to a certain extent. Therefore, the increase in transportation, storage and post production value directly increases GDP.

2.4. Flow diagram

The causality diagram of the Beijing-Tianjin-Hebei airport group does not distinguish between state variables and rate variables, and can only reflect the influence between various variables. However, in the process of further modelling, the model needs to be quantified to distinguish different types of variables. Therefore, the system flow diagram is drawn on the basis of the causal graph, as shown in Figure 4. The passenger throughput at each airport is a state variable, and accordingly, the passenger throughput increment is increased as a rate variable.

Figure 3. The feedback loop. Figure 4. The flow diagram.

3. Case study

In this paper, the VEMSIM PLE system dynamics software is used to simulate the Beijing-Tianjin-Hebei airport group efficiency model. The data mainly comes from the 2010-2017 Civil Aviation Airport Production Bulletin and the National Economic and Social Development Bulletin. The historical data is eight years long and the forecast period is five years from 2018 to 2022, with a time step of one year. It mainly includes the following data:

- GDP (2010–2017);
- Regional permanent resident population (2010–2017);
- Passenger throughput in three airports (2010–2017).

3.1. Structural equation

\begin{align}
L\ AFP.P & = AFP.J + AFPI.JK \\
N\ AFP & = 7394.81 \\
N\ ASP & = 727.71 \\
N\ ATP & = 272.36 \\
R\ AFPI.JK & = 27.401*FIPR.J +33.221*AGDP.J + 34.875 \\
R\ ASP.JK & = 22.078*SBSP.J +180.635*AGDP.J – 47.425 \\
R\ ATPI.JK & = 24.422*TLCC.J +4.3*TBSP.J +18.162*AGDP.J – 80.119 \\
A\ RTP.K & = AFP.K + ASP.K + ATP.K \\
A\ TSPPV.K & = 0.284*RTP.K +1003.05 \\
A\ GDP.K & = 27.578*TSPPV.K – 44973.9 \\
A\ AGDP.K & = GDP.K/RP.K
\end{align}
\[ A \, FE.K = AFP.K/FC \]  
\[ C \, FC = 8550 \]  
\[ C \, SC = 2500 \]  
\[ C \, TC = 2000 \]  
\[ A \, FIPR = TABLE(TFIPR, \text{TIME}, 2010, 2022, 1) \]  
\[ FW.K = AFP.K/(AFP.K + ASP.K + ATP.K) \]  
\[ E.K = FW.K * FE.K + SW.K * SE.K + TW.K * TE.K \]  

In the structural equation, \( L, R, A, N, C, J \) and \( K \) represents the state equation, the rate equation, the auxiliary equation, the initial value, the constant equation, the previous moment, the current moment respectively. The equations of ASP, ATP are similar with that of AFP. The equations of SE, TE are similar with that of FE. The equations of SW, TW are similar with that of FW. TFIPR indicates the value of FIPR variable over time, and the equations of SBSP, TLCC, TBSP, and RP are similar with that of FIPR.

3.2. Model checking

In order to ensure that the constructed model is consistent with the actual situation, the model can reflect the characteristics of the real system, the model results need to be compared with the historical data. If the error is within the acceptable range, the model can be used to simulate the reality and the subsequent prediction results are reasonable. In this paper, the GDP and PEK passenger throughput data from 2010 to 2017 are selected as the test objects, as shown in Table 2. The errors between the predictive value of GDP, the passenger throughput of PEK and the actual data are all within 10%, indicating that the model is constructed reasonably and can be used for the next policy analysis.

| Year | GDP actual value | Predictive value | Error absolute value | passenger actual value | Predictive value | Error absolute value |
|------|------------------|------------------|---------------------|-----------------------|------------------|---------------------|
| 2010 | 43732.3          | 45911.4          | 4.98%               | 7394.8114             | 7394.8114        | 0.00%               |
| 2011 | 52074.97         | 50907.9          | 2.24%               | 7867.4513             | 7636.31          | 2.94%               |
| 2012 | 57348.29         | 53909.4          | 6.00%               | 8192.9352             | 7884.61          | 3.76%               |
| 2013 | 62685.77         | 57656.2          | 8.02%               | 8371.2355             | 8142.24          | 2.74%               |
| 2014 | 66478.91         | 62249.5          | 6.36%               | 8612.8313             | 8411.78          | 2.33%               |
| 2015 | 69358.89         | 68130.8          | 1.77%               | 8993.9049             | 8696.65          | 3.31%               |
| 2016 | 75624.97         | 75134.5          | 0.65%               | 9439.3454             | 9002.58          | 4.63%               |
| 2017 | 82559.73         | 83708.2          | 1.39%               | 9578.6296             | 9334.37          | 2.55%               |

3.3. Simulation results

The system simulation results are shown in Table 3. From 2012 to 2014, the efficiency value of PEK was in the range of \([0.9, 1]\), indicating that the resource usage in this airport was about to reach its limit. In 2015, the efficiency value exceeded 1, indicating that PEK was overloaded. The efficiency value of TSN from 2010 to 2014 was less than 0.5, indicating that the airport's resources were redundant and not fully utilized. In 2017, the airport efficiency value tended to 1, so airport resource usage was close to saturation. The efficiency value of SJW in 2010-2017 has been below 0.5, it means that the waste of resources was serious. Since 2010, the overall efficiency of the Beijing-Tianjin-Hebei airport group has been continuously improved. In 2015 and 2016, although the efficiency of TSN and SJW has increased rapidly, the impact on overall efficiency was not as large as that of PEK due to the low weight. The efficiency of PEK has exceeded the limit in nearly three years, so the overall
efficiency was near saturation. This also shows that for PEK, measures should be taken to divert or increase capacity, and TSN and SJW should take a different approach to increase the flow.

Table 3. The efficiency value of the airport group.

| Year | FE  | SE  | TE  | FW  | SW  | TW  | E  | Year | FE  | SE  | TE  | FW  | SW  | TW  | E  |
|------|-----|-----|-----|-----|-----|-----|----|------|-----|-----|-----|-----|-----|-----|----|
| 2010 | 0.86| 0.29| 0.14| 0.88| 0.09| 0.03| 0.79| 2017 | 1.09| 0.93| 0.49| 0.74| 0.18| 0.08| 1.02|
| 2011 | 0.89| 0.31| 0.15| 0.88| 0.09| 0.03| 0.82| 2018 | 1.13| 1.32| 0.62| 0.68| 0.23| 0.09| 1.13|
| 2012 | 0.92| 0.34| 0.18| 0.87| 0.09| 0.04| 0.84| 2019 | 1.18| 1.69| 0.75| 0.64| 0.27| 0.09| 1.28|
| 2013 | 0.95| 0.40| 0.21| 0.85| 0.10| 0.04| 0.86| 2020 | 1.23| 2.13| 0.90| 0.60| 0.30| 0.10| 1.47|
| 2014 | 0.98| 0.48| 0.27| 0.83| 0.12| 0.05| 0.89| 2021 | 1.29| 2.67| 1.07| 0.56| 0.34| 0.11| 1.73|
| 2015 | 1.02| 0.62| 0.34| 0.80| 0.14| 0.06| 0.92| 2022 | 1.35| 3.32| 1.26| 0.52| 0.37| 0.11| 2.07|
| 2016 | 1.05| 0.79| 0.41| 0.76| 0.17| 0.07| 0.96|

3.4. Policy verification

For PEK, the policy that can be implemented is to expand the airport capacity. In the model, the passenger capacity of PEK is adjusted to simulate the expansion policy. The efficiency comparison before and after is shown in Figure 5. After the expansion, the efficiency value is less than 1, no more overuse. From the appearance, the efficiency value is reduced, but in fact, the congestion of PEK is reduced, the airport resources are fully utilized. So the airport efficiency is improved. The policy of expanding airport capacity is also in line with the completion of the Beijing New Airport and its operation in 2019. By then, the overall capacity of Beijing airports will be larger, which will meet the needs of passengers in Beijing.

In addition, the proportion of international passengers in PEK has increased year by year, and the flight schedule is allocated to international routes. Also, PEK tries to cancel low-efficiency flights and flights operated by 100 or less seats, or transfer them to TSN and SJW, so the positioning is more biased towards international routes. This policy is embodied in the model as the variable “International passenger ratio of PEK (FIPR)”. Although the increase in efficiency value is small after increasing the value of this variable, the change in international passenger numbers can increase the efficiency of PEK, TSN and SJW under the premise of the airport's unsaturated resources, so that the efficiency of the airport group improves. It reflects the behaviour of an airport can influence other airports and the whole airport group. Therefore, the policy of PEK towards international routes is reasonable and effective.
TSN is a supplement to Beijing Airport in terms of trunk flights, but its competitiveness is far less than that of Beijing. TSN adapts to the needs of the Beijing-Tianjin-Hebei airport group and focuses on the development of the branch network to form a route network combining trunk and branch lines. In the model, the policy is embodied as the variable “Branch shipping points of TSN (SBSP)”. Increasing this variable value, the comparison of the efficiency of TSN before and after the change is shown in Figure 6. After the adjustment, the efficiency value of TSN has increased clearly, but as the predicted passenger demand is far greater than the capacity of TSN, it may be necessary to expand capacity in the later period. The efficiency of PEK and SJW has increased slightly. The increase makes the efficiency of the airport group raise. The impact reflects the interconnectedness of the airports in the airport group. It also shows that this policy is feasible.

Increasing the number of low-cost base airlines in SJW in the model, the comparison of the efficiency of SJW before and after the change is shown in Figure 7. After the adjustment, the efficiency value of SJW has increased significantly, the impact on PEK and TSN is relatively small due to the small weights of SJW. The change make the efficiency of airport group improve overall. Changing the number of branch shipping points in SJW and changing that at TSN have similar effects on these three airports, so it will not be repeated here. Therefore, SJW needs to be positioned at low cost and on the branch lines continuously. SJW can encourage the establishment of low-cost base airlines, open low-cost routes, increase branch routes, and actively expand regional flights continuously.

4. Conclusion
The airport group is a complex system influenced by many factors such as regional economy, population, and various airports. The study of airport group efficiency needs to reflect the dynamic changes and integrity of the airport group. Compared with other methods, system dynamics (SD) can better reflect the characteristics of airport groups and simulate the internal and external impacts of airport groups. Therefore, this paper uses the system dynamics to simulate the Beijing-Tianjin-Hebei airport group and establish the efficiency model. The results show that the model is consistent with the development trend of the airport group. The overall efficiency of the airport group is increasing year by year. However, since 2015, PEK has an efficiency value higher than 1, indicating that the airport resources were overused and the airport efficiency was reduced. The efficiency of TSN has increased year by year. In 2017, the efficiency value reached 0.93, and the resources tended to be fully utilized. Similarly, the efficiency of SJW has increased, but it still has not reached the efficiency value of 0.5, and the waste of resources was serious. Then, the paper verifies the internationalization of PEK, the combination of TSN's trunk-branch lines, the low-cost and branch positioning of SJW, and finally proves that these policies are reasonable and feasible. At the same time, the policy proposed to expand the capacity of PEK in this paper coincides with the construction of the new airport in Beijing. Through the subjective regulation of these policies, it is possible to promote the relatively balanced
service of the airport group, and avoid the situation of excessive accumulation of aviation resources in PEK. Research on the efficiency of airport groups based on system dynamics fully reflects the inseparable links between airports in the airport group and the integrity of the airport group.

This paper is a preliminary exploration of the efficiency of the airport group. Further studies on it and policy analysis can be more in-depth, including:

1. The research can introduce other airports into the SD model of airport group efficiency;
2. Establish a SD model with more factors;
3. This paper uses the flow capacity ratio to define efficiency, and how to define efficiency more rigorously needs further study.

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