International Journal of Technology (2015) 5: 733-742
ISSN 2086-9614

SYSTEM DYNAMICS MODEL FOR AIRPORT CHARACTERIZATION IN HUB-AND-SPOKE NETWORKS

Eny Yuliawati[1*], Sigit P. Hadiwardoyo[1], Bambang Susantono[1], Tri Tjahjono[1]

[1]*Department of Civil Engineering, Faculty of Engineering Universitas Indonesia, Kampus Baru UI Depok, Depok 16424, Indonesia*

(Received: May 2015 / Revised: November 2015 / Accepted: December 2015)

ABSTRACT

Global revenue by passenger kilometers over the last ten years has grown at an average of 4.7 percent per year. The high growth of air transport must be offset by equivalent airport investment: perhaps even a doubling of the percentage growth of numbers of passengers. The purpose of this paper is to build a development model for investment in hub-and-spoke airport networks. The methodology developed in this paper uses systems dynamics theory. The benefit of using this approach is that the variables in the model are determined through a systems thinking process; the determination of variables through such a thinking process considers causality between variables dynamically, logically, and realistically within a complex aviation industry system. The simulation model shows that using a system dynamics approach can be used to simulate airport infrastructure investment development in a hub-and-spoke network. One of the subsystems is congestion; the result of simulation of this subsystem yields the behavioral characteristics, which show that a surge in demand (which is then offset by the provision of capacity or capacity enlargement) will eventually become stable, indicated by a lack of lines on the runway side. This means that decreases in congestion will increase passenger demand, and will also enhance potential investment in airport infrastructure.

Keywords: Airport characterization; Airport infrastructure; Congestion; Hub-and-spoke network; System dynamics

1. INTRODUCTION

Revenue passenger kilometers (RPKs) around the world grew at an average of 4.7 percent per year over the past ten years (2000–2010); in Southeast Asia, RPK growth during the same period was 6.6 percent per year (Badan Litbang Kementerian Perhubungan, 2012). This shows that the rate of traffic growth in Southeast Asia during this period exceeded the growth rate of the rest of the world. The growth of air passengers in Indonesia, as a part of that region, is very promising, with the numbers of passengers who use air transport at 80 million/year; with approximately 6 percent of the population of Indonesia using air transportation, investment in airport infrastructure is necessary. Transport has a stronglypositive influence on economic development (Irwin & Kasardah, 1991; Button & Taylor, 2000; Van den Berg et al., 1996).

In Indonesia, airport infrastructure can be differentiated by function, utilization, classification, status, type of management, and type of activities. Based on a hierarchy of functions, airportscan be grouped into the "hub" or "spoke" airport categories. Hub airports can be distinguished by their service scale (primary, secondary, and tertiary), depending on the

* Corresponding author's email: enjulia_2005@yahoo.co.id, Tel. +62-21-7270029, Fax. +62-21-7270028
Permalink/DOI: http://dx.doi.org/10.14716/ijtech.v6i5.1039

importance of traffic, and especially based on the number of passengers. In the context of hub classification, determining the contribution of each airport to the national network is a key aspect of traffic generation and connectivity. Spoke airports are "collectors," and they serve as support infrastructure in servicing the public at the local level. Hub-and-spoke operations are typically achieved by consolidating "originating" and "transfer" passenger flows (Doganis, 2010; Button, 2002), which implies the existence of two dimensions of "hubbing" traffic generation and connectivity. Generated traffic is traffic between hub airport "H" and airport "A," while connecting traffic is traffic between airport A and airport B via hub airport H. According to Liu et al. (2006), most hubs are located in regions with large local markets. Soekarno-Hatta Airport in Jakarta is an example of an international airport (hub), while Ngurah Rai Airport in Bali and Juanda Airport in Surabaya are both considered to be regional international airports.

The rapid growth of air passengers must be balanced by the provision of air transportation infrastructure, but governmental budgets in the transportation infrastructure sector face constraints. In budgeting for the airport infrastructure sector, the Indonesian government only allocates Rp 19.5 trillion/5 years, while the necessary budget for the development of 233 airports amounted to Rp54 trillion/5 years; thus there is a financing gap of Rp 34.5 trillion, or 63 percent of the budget requirements (DGAC, 2010). Because the development of airports in Indonesia is still a burden, the government needs to use policy instruments if it wants to involve the private sector in airport development. One policy instrument is to define a model of air passenger demand using a dynamic systems approach to support the financial analysis of the development of airport infrastructure in a hub-and-spoke network.

The advantage of a demand model for airport investment analysis in a hub-and-spoke network using a dynamic systems approach is the variables for measuring the potential demand that are determined through systems thinking: namely, the determination of the variables with a "mental model" that considers the causality relationship between variables (Wirjatmi Endang, 2004). A robust model could support the analysis of decision making in airport development in a hub-and-spoke network that would involve the participation of private investment.

The purpose of this paper is to develop a model for investment in a hub-and-spoke airport network. The system dynamics approach will be applied to the design of the model. The benefit of a model using a system dynamics approach is that the variables in the model are determined through a systems thinking process. The determination of variables with such a process considers the causality between variables dynamically, logically, and realistically in a complex aviation industry system. Considering the complexity of the aviation system can help us better understand the decision-making process when considering whether or not to provide new airport infrastructure, or to enlarge existing infrastructure.

2. METHODOLOGY

The research methodology used in this study is based on a comprehensive literature review of data collection and systems dynamics as quantitative tools for data analysis. Systems dynamics (SD) was developed by Jay Forrester at the Massachusetts Institute of Technology in the 1950s; it describes cause-effect relationships, time delays, and feedback loops, all of which factor into the unexpected behavior of complex systems (Ogunlana & Sukhera 2003).

The research process employed for this work is the establishment of a simulation, as shown in Figure 1. The first step is problem structuring, using a stock flow diagram and a causal loop to determine the interaction variables, based on a theoretical concept (building the mental model/system thinking). The second step is data collection to validate the model and the structure of the model versus the structure of factual data, and to validate the performance model versus the actual performance. The third step is dynamic modeling to simulate the model, which includes the external variables that will have the largest impact on the performance model; the purpose of this is to define the best possible strategic alternatives. The final step is scenario planning and modeling in order to create scenarios with sensitivities tests, meaning that the simulation model includes any predictable variables that might affect the sensitivity of the model.

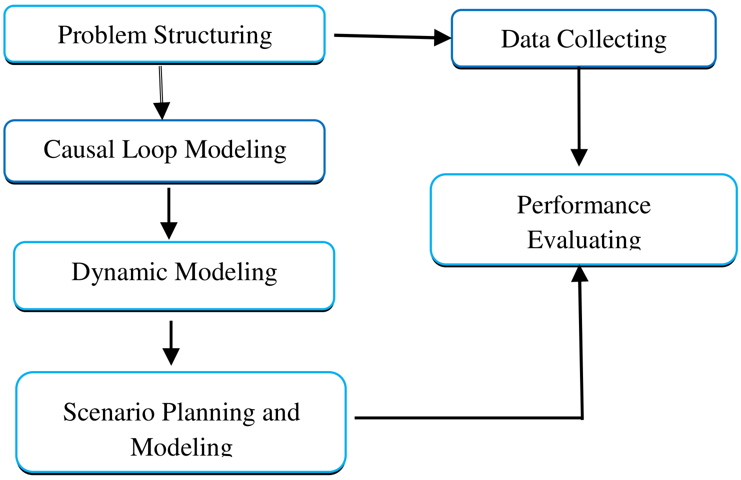

Figure 1 Flow of the research framework

The next step is building a simulation model through "stock flow" diagrams. Using this diagram, the behavior of all the variables that form the subsystem can be measured, and interaction variables can be observed within and between subsystems. The model can represent the system in real conditions, so that the results of simulation models can be used when considering policy decision-making steps. Running the model through the year 2030 yields two scenario options: optimistic and pessimistic scenarios. Building the cause-effect or causal loop diagrams creates a visual representation of the interactions and feedback loops between different variables that affect air passenger demand rates. Causal loop diagrams identify variables that will be used in the stock flow diagrams, and illustrate how each variable can affect the outcome directly or through other intermediate variables. In order to build the causal loop model, there are five loopings; the loopings in the causal loop diagram are described as follows.

Looping B1 (Balancing) describes the condition of the population factor that is affected by birth and death rates. The equation for the population factor (Valerijs, 2010) is as follows:

$$PG_t = P_t\left[\left(\sum_{i=1}^{N} B_t\right) - \left(\sum_{i=1}^{N} M_t\right)\right] \tag{1}$$

The subsystem population in Equation 1 (PG) is defined as population growth; P is population, B is birth rate, M is mortality rate, N is forecasting year, i is initial year, and t is time period of the forecast.

Looping B2 (Balancing) describes the condition of air traffic congestion and airfare impacts that affect one another in the number of flights and air passenger demand. Congestion is defined as waiting time for every aircraft that uses the runway. The equation of congestion (Larson & Odoni, 1981) and airfare impact (Belobaba, 2001) are described as follows:

$$\mathrm{Wq} = \frac{\lambda.\left[\left[\frac{1}{\mu}\right]^2 + \sigma t^2\right]}{2.\langle 1-\rho\rangle} \tag{2}$$

$$\rho = \frac{\lambda}{\mu} \tag{3}$$

$$\mathrm{AI} \;=\; \varepsilon\,\mathrm{Pr} \;\times\; \Delta\,\mathrm{TC} \tag{4}$$

Model congestion is defined as Wq; Wq is waiting time for each aircraft that wants to land or take off on the runway, where λ is the average number of flights, σt^2 is the standard deviation of service time, μ is runway capacity, and ρ is the utilization ratio. In the next equation, AI is defined as airfare impact, where ε Pr is the price elasticity of demand, and $\Delta\,\mathrm{TC}$ is the percentage increase in travel costs as an impact of congestion cost.

Looping R1 (Reinforcing) describes the condition of the gross regional domestic product (GDRB) factors that affect the number of air passengers per year.

Looping R2 (Reinforcing) describes the condition number of annual air passenger demand, which is influenced by the factors of population and GDRB growth

$$\mathbf{G_{(t)}} = \mathbf{G_{(t-dt)}} + (\Delta\,\mathbf{G}) * \mathbf{t(5)} \tag{5}$$

$$\Delta\,\mathbf{G} = \frac{\mathbf{Ggr}}{\mathbf{100}} \times \mathbf{G}\;(\mathbf{6}) \tag{6}$$

The subsystem GDRB represents the gross regional domestic product of the review region (airport area). In Equations 6 and 7 (Valerijs, 2010), G is defined as GDRB, Δ G is change of GDRB, Ggr is GDRB growth, and t is defined as time.

Further, based on data from the National Airport System in Indonesia (Ministry Regulation, 2013), Table 1 shows 2014 airport data in the categories of function and utilization in the largest Indonesian islands.

Table 1 The number of airports in Indonesia by function and utilization (Indonesian Airport System, 2014)

No	Island in Indonesia	Domestic		International	
		Hub	Spoke	Hub	Spoke
1.	Sumatera	5	26	6	1
2.	Jawa	0	9	7	0
3.	Bali-Nusa Tenggara	0	16	3	0
4.	Kalimantan	3	28	3	0
5.	Sulawesi-Maluku	3	26	2	0
6.	Papua-Maluku	2	93	2	2
	Total	237			

Indonesia has 237 airports on 6 major islands. In order to develop our dynamic modeling, we use data from the period 2004–2012. The sample observation forthe primary hub airport is Sam Ratulangi Airport in Manado; the secondary hub airport is Adi Sutjipto in Yogyakarta; and the tertiary hub airport is Husein Sastranegara in Bandung; the spoke airport is Juwata Airport in Tarakan. The supporting data for system dynamic modelling is shown in Table 2.

Table 2 Hub-and-spoke airports with their profiles (Survey data, 2014)

Airport criteria	GDRB growth (%)	Passenger growth (%)	Runway capacity (aircraft)	Avtur* price/lr (Rupiah)	Airfare average (Rupiah)	Airport tax (Rupiah)	Cost landing/ton (Rupiah)	Aircraft type provided
Primary Hub	0.1299	0.0782	192	12,000	1,252,000	35,000	388,500	Wide-body, Narrow-body, Regional jets
Secondary Hub	0.1115	0.1442	168	12,000	1,200,000	35,000	325,900	Narrow-body, Regional jets
Tertiary Hub	0.1354	0.0999	144	12,000	1,095,714	30,000	44,000	Narrow-body, Regional jets
Spoke	0.1172	0.2713	96	12,000	939,000	11,000	4,000	Regional jets

* Note: “avtur” = “aviation turbine fuel”

The criteria of hub-and-spoke airports are based on the number of passengers (hub airports 500,000 ≤ X ≤ 5 million passengers/year, and spoke airports less than 500,000 passengers/year). Another categorization is possible when the type of utilization is considered as a criterion. Airports can be grouped into two different categories: international airports and domestic airports; the former serve both domestic and international flights, while the latter serve only domestic flights. If status is considered, the airport can be categorized into public airports and special airports.

Indonesia has a large number of airports; few of them can be considered national hubs or connection nodes for the country. Most connect to frontier spots inside the web of airport infrastructures in Indonesia; the second degree of openness toward outside countries concerns very few of them. The majority of airports are oriented toward domestic considerations. We have to conclude that airport situation is hugely segmented, which has several implications in terms of traffic and connections with outside countries, and their roles as nodes. Obviously, this high level of diversity has consequences for the business of each category of airport infrastructures, but also for the interest of the private sector in investing in such projects. The implications for the institutional framework have to be taken into consideration (Carnis & Yuliawati, 2013).

3. RESULTS AND DISCUSSION

The model that was designed has five subsystems, as was explained in the methodology section. Unfortunately, due to space limitations in this paper, it is not possible to present all subsystems and their variables. The paper will thus present those subsystems that are considered crucial in the model.

The "congestion" subsystem is defined as the waiting time for each aircraft that wants to land or take off on the runway. The variables that interact in the subsystem are the average number of flights, the standard deviation of service time, runway capacity, and the utilization ratio. The results of simulations using the system dynamics approach is behavior over time (BOT). As shown in Table 3 and Figure 2, for airport congestion at the primary hub airport, congestion that occurred at the beginning of the review had a duration of 0.29733 hours; at the secondary hub airports, the duration was 0.87069 hours; the tertiary hub airports had a duration of 0.20998 hours; and the airport spoke had a duration of 0.19968 hours. At the begining of the review period, the congestion that occurred at airports in the hub-and-spoke network showed an increasing trend, and in subsequent periods tended to be stable.

Table 3 Dynamic modelling behavior over time of congestion at hub-and-spoke airports

Years	Congestion				Annual Air Passenger			
	Spoke	Hub Tertiary	Hub Secondary	Hub Primary	Spoke	Hub Tertiary	Hub Secondary	Hub Primary
1	0.19968	0.20998	0.87069	0.29733	76,857	77,069	579,865	387,645
2	0.20217	0.22628	0.93110	0.34431	83,315	118,647	918,781	501,698
3	0.20717	0.24541	0.99401	0.39612	96,226	166,701	1,259,904	622,963
4	0.21470	0.26750	1.05959	0.45323	115,579	221,204	1,603,233	751,408
5	0.22482	0.29272	1.12799	0.51616	141,358	282,133	1,948,765	887,009
6	0.23758	0.32125	1.19940	0.58553	173,544	349,466	2,296,500	1,029,747
7	0.25306	0.35330	1.27403	0.66208	212,115	423,185	2,646,434	1,179,610
8	0.27137	0.38914	1.35207	0.74667	257,049	503,271	2,998,568	1,336,586
9	0.29263	0.42906	1.43378	0.84032	308,325	589,713	3,352,900	1,500,666
10	0.31699	0.47341	1.51940	0.94427	365,923	682,497	3,709,429	1,671,844
11	0.34462	0.52260	1.60922	1.06000	429,827	781,615	4,068,154	1,850,115
12	0.37574	0.57712	1.70356	1.18928	500,021	887,059	4,429,075	2,035,474
13	0.41060	0.63753	1.80276	1.33432	576,494	998,822	4,792,190	2,227,918
14	0.44947	0.70449	1.90719	1.49782	659,234	1,116,900	5,157,499	2,427,445
15	0.49270	0.77880	2.01727	1.68317	748,233	1,241,287	5,525,001	2,634,052
16	0.54069	0.86137	2.13347	1.89467	843,486	1,371,982	5,894,696	2,847,737
17	0.59389	0.95335	2.25631	2.13783	944,987	1,508,982	6,266,584	3,068,500
18	0.65284	1.05608	2.38637	2.41987	1,052,732	1,652,285	6,640,663	3,296,338
19	0.71818	1.17121	2.52429	2.75039	1,166,719	1,801,888	7,016,933	3,531,251
20	0.79066	1.30075	2.67080	3.14250	1,286,944	1,957,792	7,395,395	3,773,238
21	0.87118	1.44722	2.82673	3.61450	1,413,407	2,119,995	7,776,047	4,022,299
22	0.96080	1.61375	2.99299	4.19280	1,546,107	2,288,496	8,158,889	4,278,433
23	1.06081	1.80435	3.17065	4.91693	1,685,044	2,463,296	8,543,921	4,541,639
24	1.17275	2.02417	3.36091	5.84885	1,830,216	2,644,393	8,931,143	4,811,918
25	1.29853	2.27998	3.56514	7.09149	1,981,625	2,831,789	9,320,555	5,089,270

In theory, the behavior of dynamic systems is categorized by the behavior of the "S curve," which indicates the results of positive and negative feedback loops as an impact on one another. It could be argued that the behavioral characteristics represented by the S curve show a surge in demand, which is then offset by the provision of capacity or potential capacity before it eventually becomes stable.

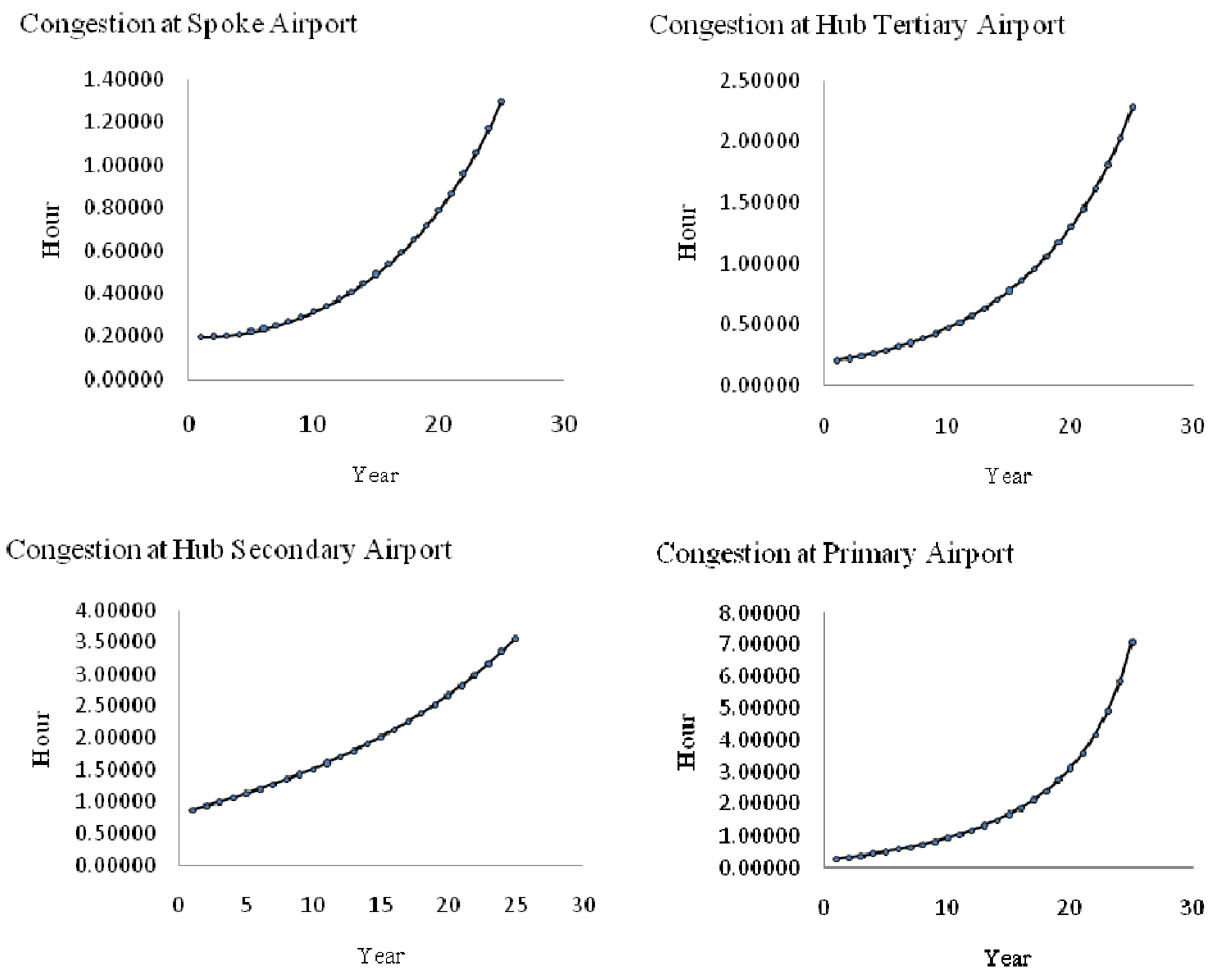

Figure 2 Behavior Over Time (BOT) of airport congestion in a hub-and-spoke network

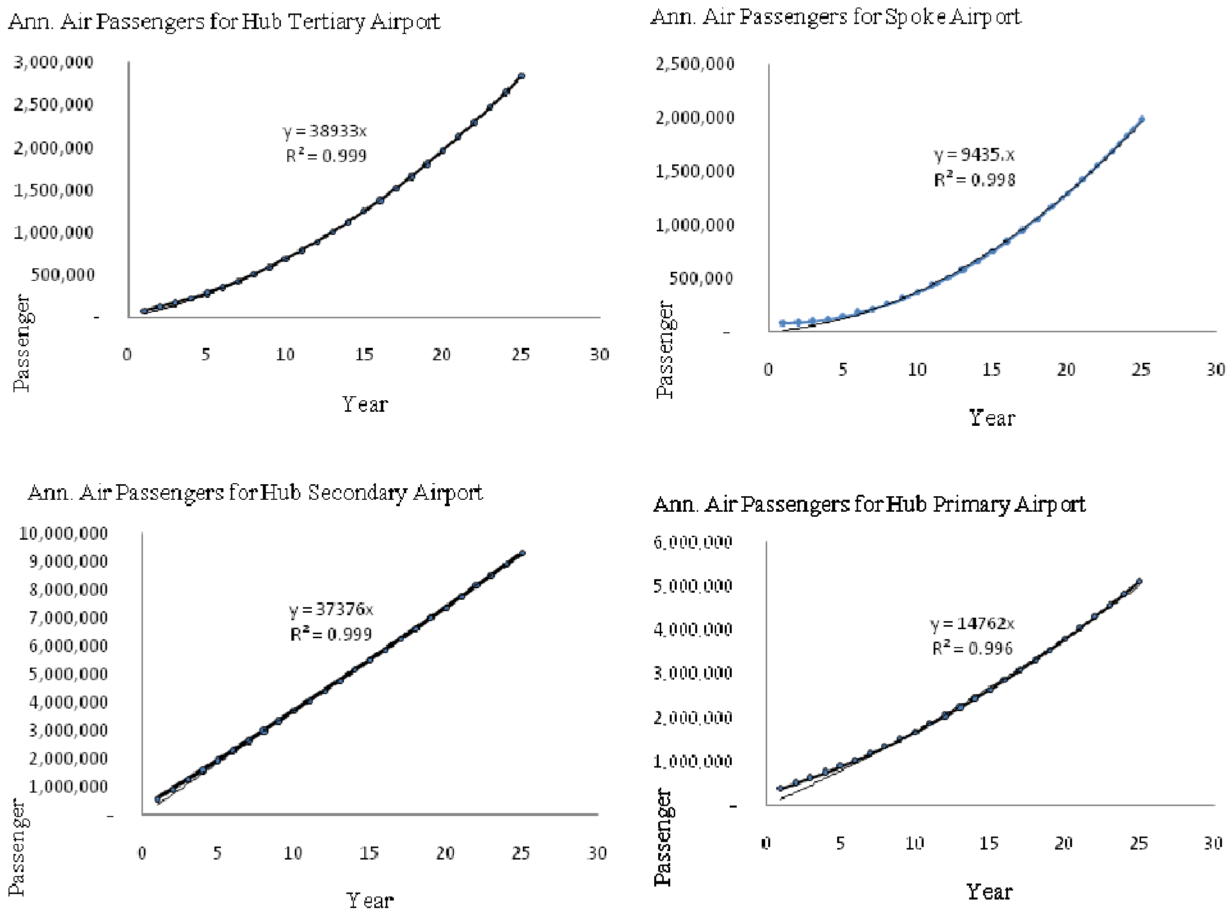

Figure 3 Behavior Over Time (BOT) of annual air passenger demand in a hub-and-spoke network

Figure 2 (the congestion behavior subsystem) indicates lines at the runway; the impact is congestion costs incurred by airlines that serve that airport. The onset of congestion costs will cause increased flight costs, which will also indirectly affect fares. The behavior of the congestion subsystem indicates the traffic jump on the runway side; its impact is congestion costs incurred by airlines that serve the airport. The onset of congestion costs causes increased flight costs, which will also indirectly affect fares.

Figure 3 shows that congestion will affect annual air passenger demand; the explanation for this is based on the theory of elasticity approach, which indicates the impact of tariff increases on the amount of air passenger demand. Therefore, the impact of congestion on the runway side will also affect the amount of annual demand for air passengers at the airport. Furthermore, passenger air transport demand models can be used to derive airport revenues. Evaluating the cost/benefits calculations tells us whether or not the private sector should participate in the development of infrastructure investments at airports.

Another step is designing a scenario model for determining performance. The scenario of the model uses several parameters, including rate of growth of GDP, growth rate of air transport, and a few other parameters. The function of the scenario is to check existing airport capacity to see if its capacity will be available for future demand.

4. CONCLUSION

Airport infrastructure development is done based on the growing number of air passengers. There are several subsystems for defining a causal loop diagram, including (among others) the factors of GDRB growth, annual air passengers, the impact of airfare, congestion (lines), and financial instruments.

The congestion subsystem is affected by the standard deviation of service time (both during take-off and landing), the average number of flights, and runway utilization. The variable of airport revenue is affected by passenger facility charges, as well as landing costs and maintenance costs of the runway. The congestion subsystem is affected by the standard deviation of service time (both during take-off and landing), the average number of flights, and runway utilization. The variable of airport revenue is affected by passenger facility charges, as well as landing costs and maintenance costs of the runway.

5. ACKNOWLEDGEMENT

The author would like to thank the Indonesian Ministry of Transportation for its very helpful air transportation supporting data, and to my supervisors, who provided comments and suggestions on earlier versions of this paper.

6. REFERENCES

Badan Litbang Kementerian Perhubungan, 2012. *Upaya Memenuhi Pertumbuhan Permintaan Jasa Angkutan Udara Penumpang*. Roundtable discussion, Jakarta (in Bahasa)

Belobaba, P., 2001. *Characteristics of Air Transportation Markets and Demand for Air Travel*. Lecture notes from "The Airline Industry" course taught at the Massachusetts Institute of Technology

Button, K., Taylor, S. 2000. International Air Transportation and Economic Development. *J. Air Trans. Manag.*, Volume 5(1), pp. 53–59

Button, K., 2002. Debunking Some Common Myths about Airport Hubs. *J. Air Trans. Manag.*, Volume 8, pp. 177–188

Carnis, L., Yuliawati, E., 2013. Nusantara: Between Sky and Earth Could the PPP be the Solution for Indonesian Airport Infrastructures? *Case Studies on Transport Policy*, Volume 1, pp. 18–26

DGAC, 2010. Ministry of Transportation Indonesia, Jakarta

Doganis, R., 2010. *Flying Off Course: The Economics of International Airlines (4th Ed.)*. Routledge, London

Irwin, M.D., Kasarda, J.D., 1991. Air Passenger Linkages and Employment Growth in US Metropolitan Areas. *Am. Soc. Rev.*, Volume 56(4), pp. 524–537

Larson, R., Odoni, A.R., 1981. *Urban Operation Research*. Englewood Cliffs, NJ: Prentice Hall

Liu, Z-J., Debbage, K., Blackburn, B., 2006. Location Determinants of Major US Air Passenger Markets by Metropolitan Area. *J. Air Trans. Manag.*, Volume 12, pp. 331–341

Mezhepoglu, B., Sherry, L., 2006. *Portfolio Analysis of Air Transportation Infrastructure Investment*. Transportation Research Board, 2007 Annual Meeting

Ministry Regulation, 2013. Indonesian Airport System No. 69 of 2013

Ogunlana, S.O., Li, H., Sukhera, F.A., 2003. System Dynamics Approach to Exploring Performance Enhancement in a Construction Organization. *J. Constr. Eng. Manag.*, Volume 129(5), pp. 528–536

Valerijs, S., 2010. Investments Model Development with the System Dynamic Method. *MPRA Paper* No. 27235

Van den Berg, L., Van Klink, H.A., Pol, P.M.J., 1996. Airports as Centres of Economic Growth. *Trans. Rev.*, Volume 16(1), pp. 55–66

Wirjatmi Endang, T., 2004. *Model Kinerja Pelayanan Public dengan Pendekatan Systems Thinking dan System Dynamic*. Universitas Indonesia, Depok. (in Bahasa)