Chapter 71
Comparison of Adoption Rates of Hydrogen, Hydrogen-Electric and SAF in the Future Air Transport System with a System Dynamics Model

Chetan Talwar, Imke Joormann, and Thomas S. Spengler

Abstract Aviation has been criticized for its negative climate impact in the past few years due to the emission of harmful greenhouse gasses (GHGs) such as CO_2, NO_x and water vapor that can cause the formation of climate harming ozone and contrails. In recent years, many different technologies have surfaced that have the potential to reduce emissions and replace the existing conventional jet fuel technology. On one hand, H_2 powered aviation just recently regained high attention from the industry, e.g., Airbus launched the ZEROe program where they pledged to develop the world's first zero-emission commercial aircraft by 2035. On the other hand, sustainable aviation fuels (SAF) or biofuels have been identified as an alternative option. Given the different promising future technologies, it is difficult to predict their role in transition pathways that will lead the air transport system towards a more sustainable future. We develop a global scale system dynamics air transport system simulation model and incorporate components like the new potential technologies, production side emissions of new fuels, i.e., SAF and hydrogen, air travel demand, airline industry and aircraft manufacturers. We also include the long, medium and short haul segments of flights. Using this model, we analyze the adoption trends of new technologies and fuels by assessing the amount of fleet operated with them and its effect on emission reduction within each flight segment.

Keywords System dynamics and theory · Dynamical systems · Transportation

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Introduction

Aviation is one of the most important industries on the planet in terms of efficient transportation. Due to the harmful greenhouse gas emissions, IATA passed a resolution for aviation to reach net-zero carbon emissions by 2050. It is widely accepted that this goal cannot be reached by using the current jet fuel technology. On the other hand, new technologies like hydrogen, hydrogen-electric and sustainable aviation fuels (SAFs) have showcased their potential, but it is unclear how the transition to these new technologies would happen if assessed strictly from a usage point of view. Furthermore, it is important to analyze what would be the behavior of the system in different adoption scenarios of these new technologies to find out their emissions reduction potential. To determine the adoption rates, the interaction between different stakeholders of the air transport system needs to be considered to understand the advantages, limitations, and potential delays of the new technologies. For example, when considering the adoption of SAF by airlines, the availability of synthetic and biofuels is a major cause of concern, as there are scalability issues [1]. In this study, a system dynamics air transport system (ATS) model is used to analyze and compare the behavior of the system under different adoption rate scenarios. The dynamics describing the ATS are influenced by feedback loops, time dependencies, stakeholder interactions, decision processes, and non-linearity. Due to its highly interactive and feedback approach, system dynamics is well suited to assess the air transport system. To consider these interactions in a dynamic simulation model, it is imperative that the mutual causality between the variables of interest is clearly defined. In this paper, the feedback structure between the variables in the ATS is described with the help of causal loop diagrams that affect the adoption of novel energy supply systems. In the system dynamics methodology, the causal loop diagram (CLD) is one tool which aids in representing the feedback structure of how different variables of interest in a system are causally interrelated [2]. The different variables from the subsystem interact with each other and affect the adoption rates of new technologies. Representing the system in this way facilitates a better understanding of the initial impression of possibilities with respect to the feedback structure within the system.

Literature Review

The system dynamics (SD) technique has been used by researchers in the commercial jet aircraft industry to demonstrate its effectiveness in forming reliable forecasts, identifying key variables for poor returns and cyclical behavior in the industry [3–5]. These models were later extended to study the potential of reducing CO_2 emissions with the help of alternative fuels in aviation [6]. For this, new feedback mechanisms like alternative fuel production, drop in quota and alternative fuel adoption mechanisms were introduced in the model. Even though the previous studies were robust and insightful, they did not include new technologies such as hydrogen and their role in different flight segments and emission reduction. Furthermore, the role of the new technologies and fuels has not been assessed in the context of recent emission goals set for the aviation industry in a system dynamics model.

Modeling Approach

The system dynamics ATS model developed previously consisted of the interlinked subsystems air travel demand, airline operations, aircraft manufacturers and alternative fuel producers [4, 6]. In this paper, the existing ATS model is used and extended further to analyze the feedback structures that affect the adoption rates of the new technologies.

The previously developed system dynamics ATS model is extended by including hydrogen and SAFs as new technologies. The model includes manufacturing capacity changes, usage adoption mechanism and production capacity changes of the new technologies. The feedback structure of the extended model is represented in Figs. 71.1, 71.2 and 71.3. In the figures, the variables given in roman are the pre-existing variables from the previous model feedback structures. The underlined and italicized variables are the new extensions made to the feedback structures. The bolded variables are the exogenous inputs that affect the feedback mechanism from the outside of the model boundary. The "+" symbol in the diagram indicates the same directional movement between the variables, while the "−" symbol indicates the relationship between variables as moving in opposite directions. The symbol "||" on the connecting lines indicates delays in the transmission of information. Finally, the variables, used more than once in the three diagrams to interlink the subsystems, are marked in green.

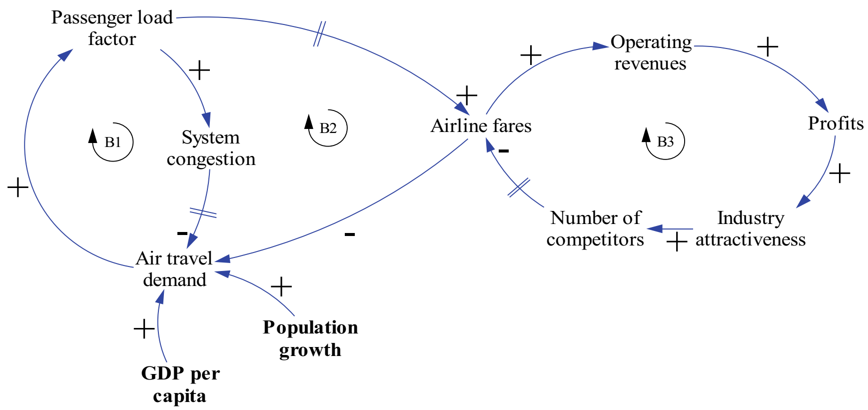

Fig. 71.1 Feedback structure between demand, passenger load factor and fares

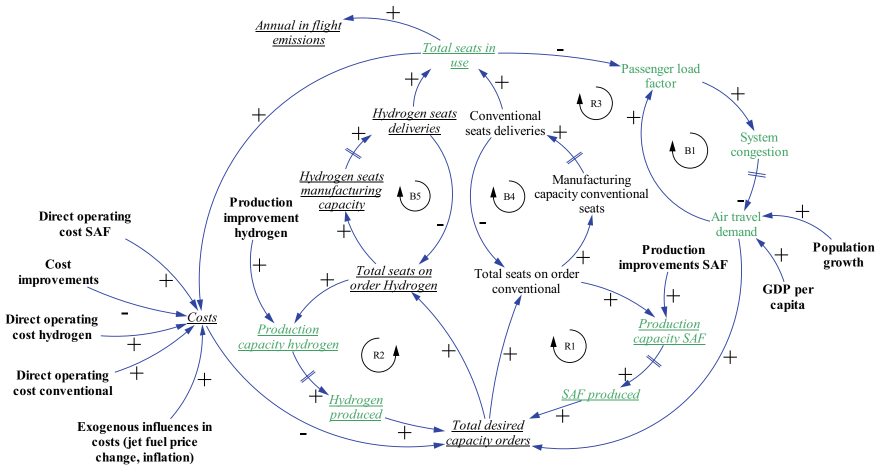

Fig. 71.2 Feedback structure of the airline fleet operation subsystem

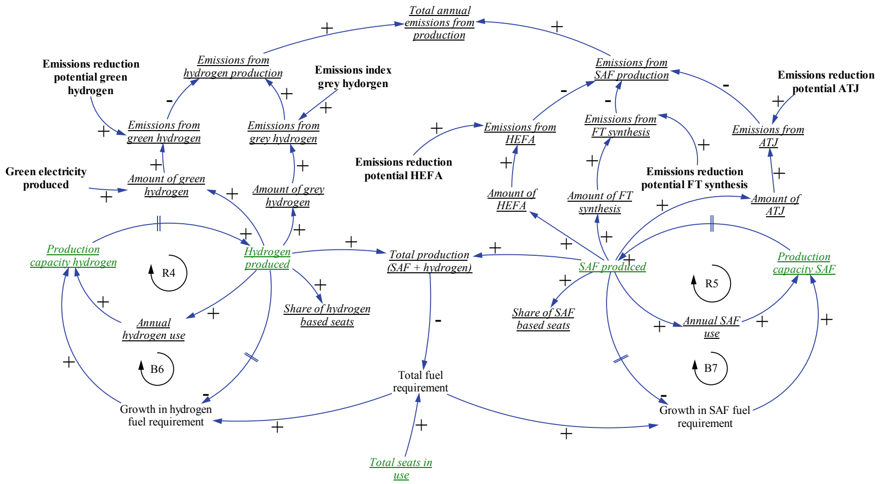

Fig. 71.3 Feedback structure of the fuel production subsystem

Figure 71.1 shows the feedback structure that leads to changes in air travel demand: First, the endogenous factors such as the effect of the passenger load factor, airline fares and profits of the industry and second, the changes in demand due to the exogenous factors like increase in population growth and GDP per capita. The balancing loop B1 shows the balancing effect of an increase in passenger load factor that increases the congestion perceived by the customers, which in turn negatively affects the air travel demand. The balancing loop B2 represents the effect of passenger load factor and ticket prices on the demand. An increase in passenger load factor positively affects airline fares. An increase in airline fares negatively affects the demand as certain customers reduce travel due to high prices. The balancing loop B3 represents the change in the attractiveness of the industry as perceived by the airlines. An increase in airline fares increases the prospected profit due to an increase in operating revenues. The increasing profits prompts other companies to enter the market, which further results in a reduction of fares to gain a higher market share.

Figure 71.2 shows the feedback structure of the airline fleet operation mechanism. The effect of air travel demand and passenger load factor from Fig. 71.1 is also taken into account. The boundaries of the previous model are extended by including feedback mechanisms related to the introduction of SAFs and hydrogen in the system.

An increase in air travel demand increases the total desired capacity orders. This is due to the action taken by airlines to increase their aircraft orders to match the demand. From this point, the extensions made to the boundary are displayed in the form of a decision to choose hydrogen based aircraft or conventional aircraft. The decision to choose one over the other depends on the direct operating costs of each technology and the fuel availability. The cost including fuel, operation, ownership of new aircraft, jet fuel prices, inflation and improvements are treated as exogenous input. The reinforcing loop R2 represents increase in the capacity of hydrogen production as the airlines choose to order more hydrogen based aircraft. With an increase in orders by the airlines, the fuel producers are incentivized to produce more as the expectation of hydrogen fuel based aircraft usage in the future increases. In order to not have unrealistic exponential hydrogen fuel production growth, the reinforcing effect of loop R2 is balanced by the balancing loop B5. In loop B5, the increase in total seats on order hydrogen increases the hydrogen seats manufacturing capacity and the amount of hydrogen seats deliveries. The increase in deliveries negatively affects the total seats on order hydrogen, which represents the adjustments done by the airlines to not over-order the fleet. Similar to loops R2 and B5, for SAF, the increase in reinforcing loop R1 is balanced by the adjustments done by the airlines in balancing loop B4. Lastly, the reinforcing loop R3 represents the steady increase in the fleet size ordered by the airlines as the demand increases depicting the growth of the industry over time.

Figure 71.3 depicts the feedback structure of the fuel production subsystem of the model. In the figure, HEFA, FT synthesis and ATJ are the acronyms used for hydroprocessed fatty acid esters and fatty acids, fischer tropsch synthesis and alcohol to jet SAF production method, respectively. The reinforcing loops R4 and R5 represent the effect of increase over time in usage of hydrogen and SAF on its production capacity changes. An increase in the amount of hydrogen and SAF produced positively affects the annual use of hydrogen and SAF. The increase in use of the new fuels provides a positive incentive for the fuel manufacturers to increase the production capacities, which after certain delays increases the amount of hydrogen and SAF produced in the system. The reinforcing loops R4 and R5 are balanced by the balancing loop B6 and B7, which depict the reduction in growth of hydrogen and SAF fuel requirement if the two technologies are adopted over time. Since the emissions from hydrogen and SAF production depend on the path through which they are produced, the bolded variables represent the emission reduction potential of different paths of production as exogenous input.

Conclusion and Future Work

In this paper, the feedback structures of the air transport system (ATS) were described with the help of causal loop diagrams (CLD). The causal loop diagrams show that if there is an increase in the airline orders of SAF and hydrogen based aircraft then it leads to an increase in SAF and hydrogen fuel production capacity. An increase in airline orders and fuel availability would over time lead to an increase in aircraft manufacturing capacity thereby generating different adoption rates of the new technologies in the system. Comparison of different adoption rates shed light on the future emissions from the system. The future challenges in developing the model lie in gathering exogenous input data, modeling the airline's decision making mechanisms, generating different adoption scenarios and developing a stock and flow model that behaves in accordance with the real system.

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