THE AIRCRAFT ENGINE GAME

- SYSTEM DYNAMICS OF THE AEROSPACE INDUSTRY

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Abstract

The civil aerospace industry features distinct systems structures. The global air traffic market is characterized by an intense competition of a high number of airlines. The relation of airlines to airframe manufacturer is currently an oligopoly with the relation of aircraft manufacturers to engine manufactures being a bilateral oligopoly. This industry is based on mature technology ensuring high levels of safety and reliability. With the lever of incremental innovation becoming smaller and smaller, the quest for technology leaps is on. Long product life cycles, additive product change, limited resources in the supply chain as well as the long lead times of a high technology environment are contradicting fast leaps in technology. In this context long term business success only is achieved by mastering the mechanisms and drivers of this very special system. Defining the products of the future requires a thorough understanding of these mechanisms and might become one of the competitive edges in product design.

Understanding of systems dynamics might be gained through digital simulations. Whilst being fast such simulations have disadvantages with regards to transparency and the interaction of entrepreneurial decisions which are shaped by the structure of the system itself. Because of that a table top simulation similarly to the beer game is proposed. The goal of the beer game was to demonstrate the effect of systems structures on the behavior of people and to show the benefits of modern supply chain management.

This paper presents major aspects of the Jet Engine Game. Its goal is to demonstrate the effect of cost, lead time and degree of innovation in the field of jet engines as well as selected changes in the industries environment on the entrepreneurial decisions of airframe manufacturers and airlines. A comprehensive specification of the Jet Engine Game is presented. Special attention is given to suitable metrics as well as the allowable degree of system simplification. The resulting limitations are documented and discussed in the light of the goals of the business simulation.

Finally typical results of the business simulation are presented. The degree of insight gained by the participants in the current development state of the business simulation is appreciated at its true value.

NOMENCLATURE

CDOC	Cash Direct Operating Costs in €
LR	Long-Range
MR	Mid-Range
RPK	Revenue Passenger Kilometer
SCM	Supply Chain Management
SR	Short-Range

1 INTRODUCTION

The global air traffic market is characterized by an intense competition of a high number of airlines. The relation of airlines to airframe manufacturer currently is an oligopoly with the relation of aircraft manufacturers to engine manufactures being a bilateral oligopoly. Long product life cycles, additive product change, limited resources in the supply chain as well as the long lead times of a high technology environment are characteristics of this industry. In this business environment it is not anymore companies but complete supply chains competing with each other. Hence planning, management and control of goods, information and capital flows requires inter-enterprise cooperation along the supply chain, an issue which is common with other supply chains [1].

Understanding the interrelations and drivers of such a complex system might be gained via business simulations. Such a simulation has been developed at the Institute for Aircraft Propulsion Systems for the application of the supply chain of the aerospace industry. It has been inspired by the “Beer Game” which has been developed by J.W. Forrester at the Massachusetts Institute of Technology in the year 1961 [2].

2 REVIEW ON SUPPLY CHAIN MANAGEMENT SIMULATION

First simulations in the field of Supply Chain Management (SCM) are introduced in the 80s [3]. The focus of the simulations is to get an understanding of the amount on material flows between supply chain stages. In this context no entrepreneurial decisions are taken into account.

Based on these simulations in the 90s continuous simulations such as iThink, VENSIM und Powersim emerged [4,5]. Connections between supply chain stages are expressed with the help of coupled differential equations. Applications therefore are in the scope of strategic network and systems design as well as the planning of resources. The simulations lack of random events such as demand fluctuation and production disturbance.

The widespread discrete simulations imply random events. Process oriented simulations as AnyLogic, Arena and Extend include a mechanism of lap time, which describe a generic life cycle of a temporary unit [7]. Another discrete supply chain simulation uses Petri Nets like CPN Tools [6]. This concept is suitable for taking auxiliary processes e.g. monitoring into account. A third group of discrete simulations, the so called Agent based simulations such as Swarm and Repast Simphony, simulate supply chain stages as "agents", which is a virtual decision maker for cooperative strategies [8]. Changes in strategies are not applicable, what prevents negotiations. Moreover the simulations lack of competitors as well as strategic networking.

Disadvantage of the described SCM simulations is the static view on company owned product portfolio without taking product development and product differentiation into account. Furthermore quality features, which are defined due to costumer demand, do not affect the duration and the costs of product development. Market potential of new ideas is also excluded in current simulations. Moreover a fully transparent supply chain is assumed which is not realistic. In addition the product portfolio of competitors, suppliers, customers need to be known in detail, which is not given in a real world context.

Nevertheless all of those simulations represent a dynamic system. The need for such dynamic simulations is an established fact.

3 NEED FOR DYNAMIC SYSTEM ANALYSIS

Bossel defines in [4], that a system is build out of separate elements, which are linked through relations. The output of one element is connected through a relation as an input on the following element, so the status of the variable within the element changes. The number of variables define the dimension of the element and the system.

Every system can be considered dynamic; hence it underlies a time sequence longer than a snapshot [4]. Within this context two dynamic behaviors have to be pointed out.

First aspect describes the change of the system state under varying frame conditions. The status of the elements can be affected directly or through the native system structure. This can lead to a feedback loop affecting the frame conditions [4]. Second aspect is caused by changing the system state because of its internal momentum. That means, the system structure itself affects the behavior within the system [9]. Even without external influences the system changes its state autonomously.

Understanding system dynamics means not only looking on the cause of an effect or development within a time and spatial frame, but also analyzing nonlinear relations, concern feedback loops and take the "history" of the system into account.

4 METHODOLOGY

Since every system can be considered dynamic, the aerospace industry is in focus of this study. The aerospace industry is characterized by high complexity, which is determined by the number of actors and their relationships substantially. To abstract the aerospace industry an excerpt of the real system was modeled using a business simulation.

Goal of the study based on the business simulation is to demonstrate the complex interactions within supply chain of the aerospace industry together with its customers the airlines and the passengers. The table top business simulation represents the sales and procurement markets in the successive stages of the supply chain of the aerospace industry as pointed out in FIGURE 1. Goods and capital flows are solely between the successive stages of the supply chain. The simulation thus provides statements about the course of capital and goods flows as a result of customer demand and the companies' business models.

The simulation time is up to twenty years in order to follow product life cycle from development to series production and product use. One year is represented by one gaming round.

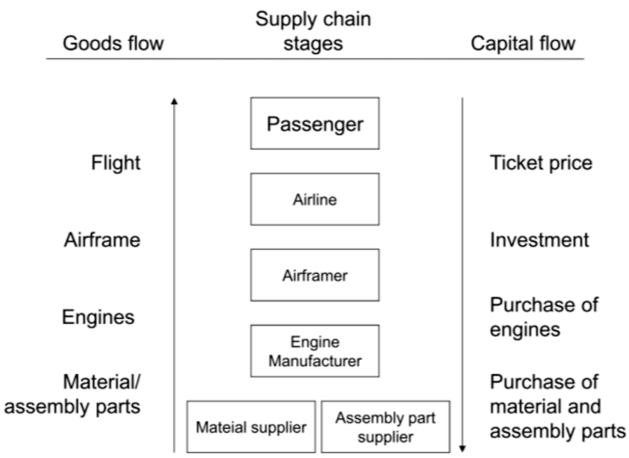

FIGURE 1. Goods and Capital Flow between Supply Chain Stages

Frame Conditions

Frame conditions for the economic situation, fuel price, raw material price and outsourcing costs allow playing the simulation under different scenarios. An example for such a frame set is given in FIGURE 2. Based on volatile trends, the impact on the dynamic system is traceable. Besides the frame condition random events are implemented to simulate political actions amongst others. An example is described in TAB 1.

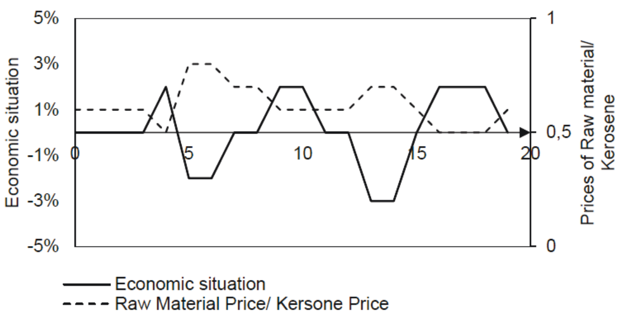

FIGURE 2. Frame condition set up

Year	Event
5	Cost for serial production of airframe manufacturer rise 20 Mio. € per airframe
8	Subsidies by government for product development of airframe manufacturers and engine manufacturers
12	Subsidies by government for purchase of airframe manufacturer with noise range +/++ for airlines
15	Airlines operating on air route London-Rome loose one aircraft due to an accident
18	The compressor outsourcing partner was declared insolvent, orders will not be fulfilled anymore, Compressors have to be produced in the engine manufacturers production

TAB 1. Example for a random event set up

Airlines

The airline's main work in the business simulation is the choice of the flight route in combination with an aircraft and an adequate ticket price. Two airlines compete in the business simulation.

To heighten the pressure of competitors for the airlines, a virtual market is included which is simulated with the help of E. Gutenberg's double kinked demand function. The demand function represents a market with monopolistic competition, respectively a heterogeneous polypoly [10]. Numerous providers form an imperfect market, where the offered products or services vary in their attributes. Because of this differentiation in product or service every provider has a monopolistic area illustrated in sector 2 of FIGURE 3. The provider can change its' price within this area, without a significant change in demand [10]. This sector is to be compared with the brand image effect of the provider. Within this sector the maximum profit can be achieved.

The choice of expensive ticket prices as in sector 1, leads to a migration of customers to the competitors. The profit decreases rapidly.

In the transition area from sector 2 to sector 3 the seat limit of the aircraft is reached. A ticket price reduction also leads to decreasing profits.

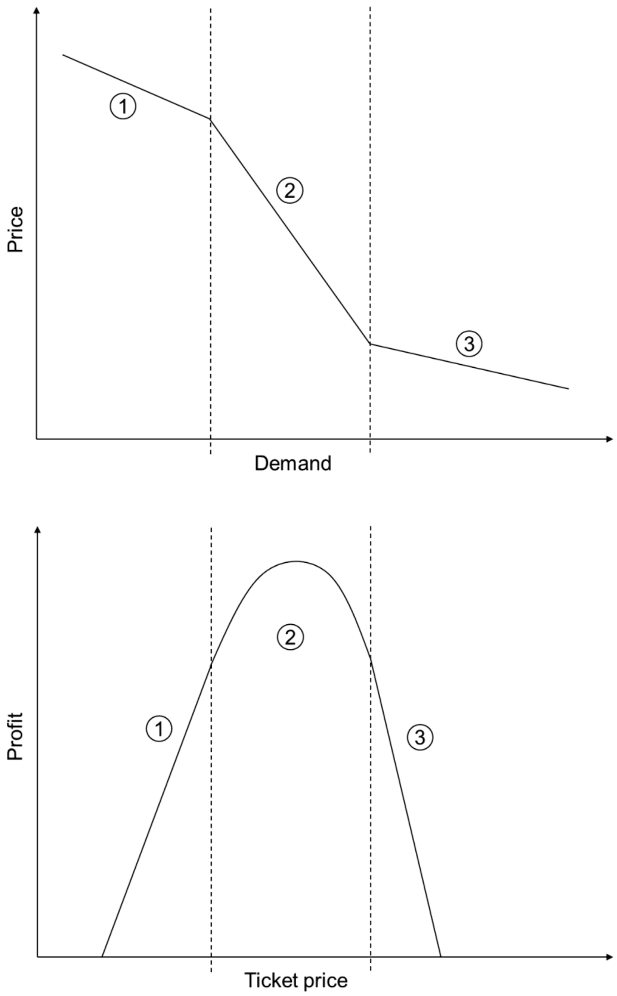

FIGURE 3. Gutenberg's demand function (above); linked profit function (below)

The profit on an air route depends on ticket prices and Cash Direct Operating Costs (CDOC). The CDOC are split into:

- Personnel costs,
- Route Costs for landing fees, insurance,
- Maintenance costs for airframe and engines and
- Kerosene Costs.

In FIGURE 4 the CDOC of two common aircrafts are compared while serving the same air route. The CDOC can be influenced by the attributes of the aircraft itself. Therefore product development of the airframe manufacturer and the engine manufacturer have to satisfy the needs of the airliners.

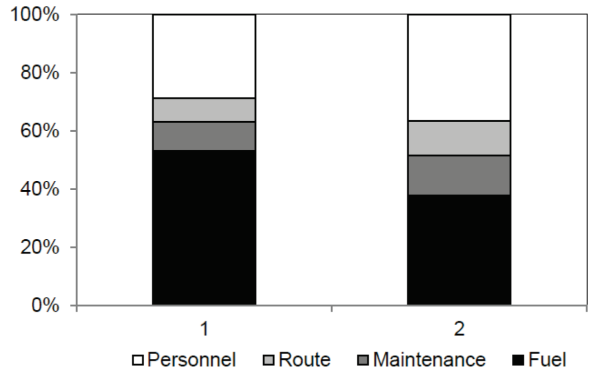

FIGURE 4. CDOC shares of two aircrafts

Airframe Manufacturer

Two airframe manufacturers embody in the business simulation the current oligopoly on the real market. Order placements for aircrafts can be set by the participating airlines and the virtual market, mentioned above.

For defining the attributes of an airframe, the airframe manufacturer has to develop products. The airframe manufacturer influences the personnel costs and the maintenance costs of the airframe. Up to the investment in time, quality and cost the attributes differ for each airframe. Once the development is completed with the certification, the attributes are fixed for serial production.

For delivering aircrafts engines have to be purchased by the airframe manufacturer. Negotiations about delivery time and price of the engines affect the end product as well.

Engine Manufacturer

Product development of the engine manufacturer is split into the modules compressor, combustion chamber, turbine, accessory parts and nacelle. For each module a decision about self-production or outsourcing has to be taken. Two outsourcing partners are modelled.

The most common motive about outsourcing is cost reduction [11]. Fix costs such as personnel costs are transformed in variable costs. The manufacturer relinquishes part the factory production control system to the outsourcing partner. The procurement risks are insolvency, raw material costs, quality defects, high prices and the delivery delay due to an enhanced supply chain.

Focus for the business simulation is the risk of a delivery delay and its influence on other supply chain stages. Therefore the function of delivery dates as illustrated in FIGURE 5 is used. The function is a left skewed distribution. Since earlier product delivery is not possible in the business simulation, only the right side of the function is used and therefore it is approximately normally distributed.

The delivery likelihood can be increased by financial investment shown in the Pareto function in FIGURE 6. Additional investments raise the value of the delivery delay reduction.

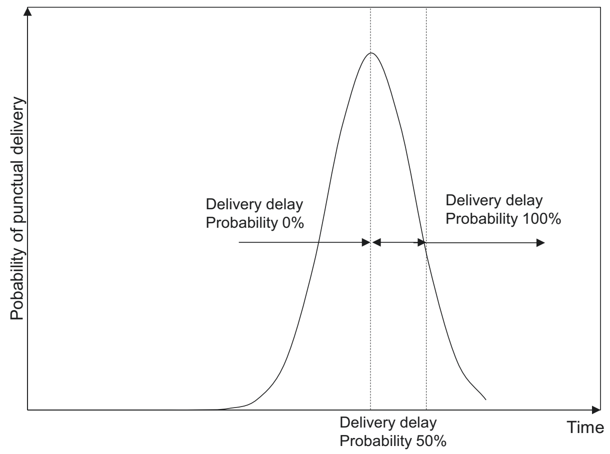

FIGURE 5. Function of delivery dates [12]

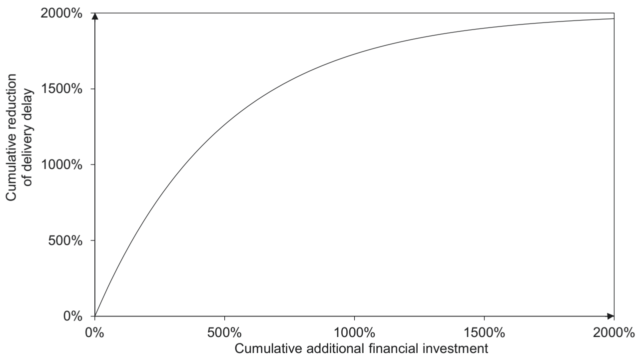

FIGURE 6. Influence financial investment on reduction of delivery date [12]

Product development influences the maintenance costs of the engines, the fuel consumption and the noise level. Outsourcing Partner 1 delivers cheaper engines but worse attributes than self-production. Outsourcing Partner 2 can develop better attributes than in self-production but higher costs and a delivery delay have to be taken for granted. After the end of product development, the outsourcing partners are also the partners for serial production. Know how transfer is not possible.

5 OBJECT OF INVESTIGATION

A scenario is presented which was conducted with six participants, distributed to the roles of the airlines, airframe manufacturer and engine manufacturers. The aim of each company was the discovery and implementation of a profit-oriented business strategy to gain competitive advantages. 18 gaming rounds, which represent 18 simulation years, were played. Every gaming round is built up as following:

1. Introduction of the event card including economic situation, raw material price and fuel price

2. Airlines: Flight operating including decision about aircraft usage on air routes and ticket prices, payment of CDOC;
   Manufacturers: Production of airframes or engines, payment for serial production costs and product development costs

3. Manufacturers: Deliveries of engines and airframes to customers, Revenues from sale

4. Profit and loss accounting

5. Negotiations about the purchase of aircrafts due the supply chain

6 RESULTS

Airlines

Airline 1 "Green Airline" represents an airline, which follows an ecological strategy to gain profits. This aim should be realized by purchasing aircrafts with low fuel demand. Airline 2 "Nice Price" is a low cost carrier, focusing on low ticket prices, high loading and aircraft purchase with quantity discount.

At the start of the simulation the airlines had cash holdings worth 1 Billion Euro. The profit of the airlines shows a reflection on the business trend of the airlines and is given in FIGURE 7.

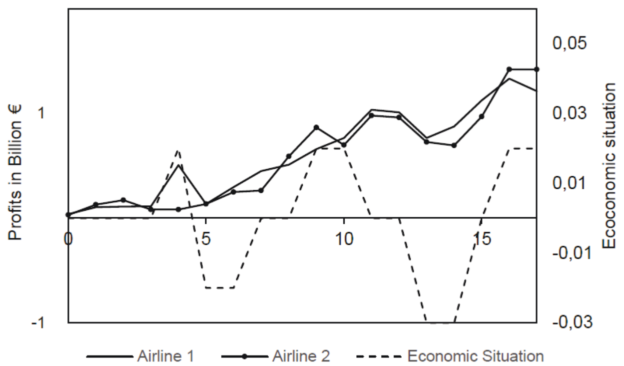

FIGURE 7. Profit trends of airlines

The profit trend of both airline is uprising due to purchase of aircrafts and new flight routes. Airline 1 purchased 15 short and mid-range aircrafts and 3 long-range aircrafts. Airline 2 invested in overall 26 short and mid-range aircrafts and 11 long-range aircrafts.

The market crises form year 4 to year 6 and from year 10 to year 14 lead to profit losses and delayed the growth of the profit. It has to be recognized that the crises only had a temporary influence on the general trend.

Due to the purchase of innovative and fuel reduced aircraft the CDOC per passenger were reduced. TAB 2 gives an overview about the CDOC per Revenue Passenger Kilometer (RPK). It has to be mentioned, that the kerosene price stayed on a constant level on the average over the simulation time.

On short and mid-range routes Airline 1 has 32% CDOC savings and on long-range routes 56%. Airline 2 reduces the CDOC on short and mid-range routes at 32% and on long-range routes at 51%. Thereby the load factor on short and mid-range was increased from 72% in year 0 to 78% in year 18. On long-range routes the load factor raised from 69% in year 0 to 91% in year 18.

	SR/MR Year 0	SR/MR Year 17	LR Year 0	LR Year 17
Airline 1	13,33 €-ct/RPK	9,03 €-ct/RPK	5,12 €-ct/RPK	2,27 €-ct/RPK
Airline 2	13,13 €-ct/RPK	8,89 €-ct/RPK	5,80 €-ct/RPK	2,84 €-ct/RPK

TAB 2. CDOC per PKM

Splitting up the CDOC a clear and similar trend in fuel savings is recognizable as given in TAB 3. Both airlines invested in innovative fuel saving aircrafts in short and mid-range and in long-range classes. For the short and mid-range aircrafts the shares of personnel, route and maintenance costs stayed almost constant. For the long range aircrafts the fuel share of the costs was reduced by one third. Almost every innovation was used to downturn the fuel consumption of the engines. The airlines did not focus on savings in the field of personnel costs and maintenance of the aircrafts, that clarifies the rise of these percent shares of the CDOC.

	SR/MR Year 0	SR/MR Year 17	LR Year 0	LR Year 17
Airline 1				
Fuel	13%	10%	46%	30%
Personnel	63%	56%	39%	48%
Route	13%	14%	4%	7%
Mainte-nance	11%	19%	12%	15%
Airline 2				
Fuel	17%	10%	46%	28%
Personnel	58%	58%	39%	55%
Route	14%	13%	4%	7%
Mainte-nance	12%	20%	12%	10%

TAB 3. CDOC shares

Airframe Manufacturer

The airframe manufacturers were separated into two companies having the same conditions in producing short and mid-range and long-range aircrafts. The aim of the companies, was to gain profit through the purchase of airframes in consultation with the airlines. Therefore the customer wishes should be addressed in terms of number of passengers, range, fuel consumption, maintenance efforts and operating costs.

As a result the profit trend of the airframe manufacturers is given in FIGURE 8. The profit trend of the airlines and the airframe manufacturer are linked by the delivery of aircrafts. If aircrafts are delivered as in year 3 in the upper diagram, the profit of the airlines increases in year 4. This trend is illustrated in the diagrams of FIGURE 8 by the arrows.

The profit trend of the airframe manufacturers is not increasing continuously as for the airlines. The airframe manufacturer has to invest in innovative airframes, what leads to a decreasing profit trend. After the airframe certification and the delivery the profits of the airframe manufacturer rise again until the next development is introduced on the market. Innovative aircrafts of Airframe Manufacturer 1 entered the airline market in year 3, year 7 and year 11 at an average of 4 years. Airframe Manufacturer 2 introduced in year 5, year 10 and year 15 new technologies on the market, what is an average of 5 years. Overall it is recognizable, that new products enter the airline market every 2 years in the business simulation.

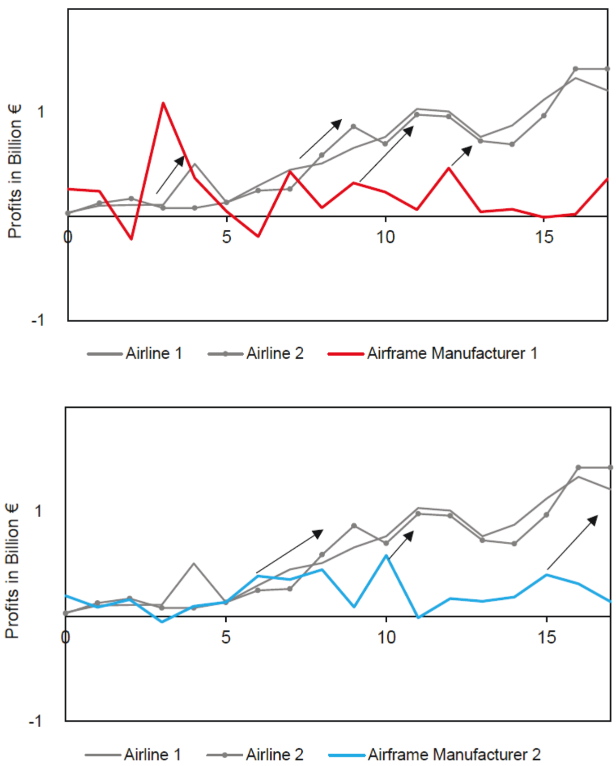

FIGURE 8. Profit trends of the airframe manufacturers in contrast to the airlines

Engine Manufacturer

The business of the engine manufacturers depends on the purchase of the airframe manufacturers. The airframe manufacturers have the choice between two engine options for most of their airframes. Aim of the engine manufacturer is to gain profit through most innovative products offers to satisfy customer needs, which are defined by the airlines. That means the engine development has to be ahead of the airframe development to give an offer about price, attributes and delivery date.

Deliveries of innovative engines started for engine manufacturer 1 in year 4, year 6, year 9 and year 13, what means an average time of 3 years for new technologies. Innovative engines of engine manufacturer 2 entered the airframe market in year 4, year 7, year 11 and year 15. Engine manufacturer 2 needs 4 years for engine development. New engines enter the market comparable to the airframe market every 2 years.

The profit trend of the engine manufacturers illustrated in FIGURE 9 has a similar volatile trend as the one of the airframe manufacturer. Due to engine development the profit decreases. After product sales the profit increases linked to new products on the market. An engine is worth 25% on average of the overall costs of the aircraft.

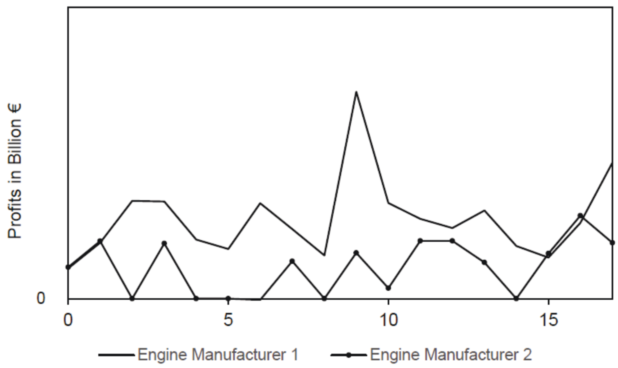

FIGURE 9. Profit trends of the engine manufacturers

As mentioned in section 4, outsourcing of engine modules is possible. To satisfy the airline requirement to reduce fuel consumption, both engine manufacturers sourced the corresponding modules out. The outsourcings of the modules lead to a cost increase of 10% for the engine manufacturers. This directly led to increased engine prices.

7 CONCLUSION

The presented business simulation is able to simulate the impact of end customer requirements on the supply chain decisions taken by the participants. Because of the long lead times a simulation time of 18 years has been evaluated. It has been shown, that the customer goal to reduce fuel consumption drives the whole supply chain consisting of airframe and engine manufacturer to reach that goal. Using the aircraft with less fuel consumption the CDOC per RPK decreased at 32% for short and mid-range routes and at 53% for long-range routes over simulation time.

Furthermore the impact of economic trends has been shown as a direct impact on the profit of the airlines. It was interesting to see, that economic crises only had a temporary influence on the general trend.

Airframe and engine manufacturer only temporarily benefit from the profit growth of the airlines. This is due the massive investment into the demanded new product development.

The insight gained through this business simulation is able to stipulate an interesting discussion about the civil aerospace industry. A comparison with real live events underlines this ability.

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