



MARMARA UNIVERSITY
INSTITUTE FOR GRADUATE STUDIES
IN PURE AND APPLIED SCIENCES



**DEVELOPING A MODEL OF AIRLINE
FLIGHT AND MAINTENANCE
OPERATIONS USING SYSTEMS
DYNAMICS APPROACH: AN
APPLICATION IN THY TECHNIC**

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Ph.D. THESIS

Department of Industrial Engineering

Thesis Supervisor

Assoc.Prof. Dr. Serol BULKAN

Thesis CO-Supervisor

Prof. Dr. Selim ZAIM

ISTANBUL, 2015



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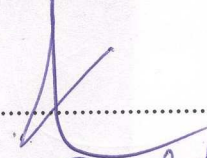
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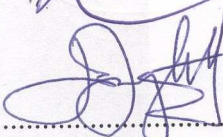
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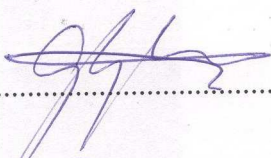
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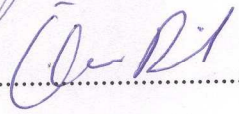
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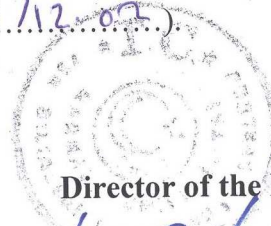
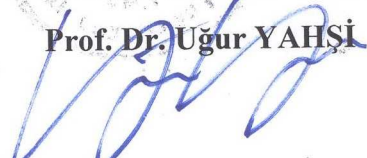
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May, 2015

Asım TOKGÖZ

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ÖZET

SİSTEM DİNAMİK MODELLEMESİ YAKLAŞIMI KULLANARAK HAVAYOLLARI UÇUŞ VE BAKIM OPERASYONLARININ MODELİNİN GELİŞTİRİLMESİ : THY TEKNİK'TE BİR UYGULAMA

Havacılık sektöründe uçakların ömrü genellikle 30 yıl civarındadır. Dolayısıyla, uçaklar bu yıllar boyunca birçok bakım hizmetlerine ihtiyaç duyarlar. Bundan dolayı, havacılık endüstrisinde elde edilen karların büyük bölümü uçağın satışından olmayıp, ömür boyu yapılan bakımdan elde edilmektedir. Bakım Onarım Overhaul (MRO) faaliyetlerinin yalın olarak maliyeti tüm maliyet bileşenleri içinde oldukça önemli yer tutmakta olup % 10 civarındadır.

Bu çalışma esas olarak Türk Hava Yolları MRO Bölümü MRO operasyonları için bir sistem dinamiği modeli geliştirmeye odaklanmıştır. Literatürdeki sistem dinamiği çalışmalardan birkaçı havayolu operasyonlarına odaklanmış olmakla birlikte, bunlarda MRO operasyonları neredeyse ihmal edilmiştir. Bu çalışma, yazarın bilebildiği kadarıyla, MRO Bölümü ile diğer havayolu operasyonları arasındaki etkileşimlere odaklanan ilk sistem dinamiği çalışmasıdır. Geliştirilen sistem dinamiği modeli, çeşitli MRO operasyonlarına ait farklı iş yükü ve uçak filosu genişleme politikalarının modellenen sanal dünyada test edilebilmesi için değerli fırsatlar sunmaktadır. Model çeşitli parametreleri kolayca değiştirerek ve farklı politikaları test ederek bir öğrenme laboratuvarı olarak kullanılabilir. Böyle bir deneme, MRO operasyon iş yükünü (kötümser, normal ve iyimser) değiştirerek ve farklı uçak filosu genişleme politikalarını uygulayarak bu çalışmada yapılmıştır.

MRO operasyonlarının, uçuşa elverişli uçakların mevcut sayısı ve filo koltuk kapasitesi üzerinde doğrudan etkiye sahip olduğu bu çalışmada bulunmuştur. Havayolu şirketleri sürdürülebilir karlı bir havayolu filosuna sahip olabilmek için mevcut ve yeni alınan uçakların MRO operasyon ihtiyaçlarını dikkate almak zorundadır.

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ABSTRACT

DEVELOPING A MODEL OF AIRLINE FLIGHT AND MAINTENANCE OPERATIONS USING SYSTEMS DYNAMICS APPROACH: AN APPLICATION IN THY TECHNIC

The life span of aircrafts is usually around 30 years in aerospace industry. So, aircrafts need lots of maintenance services in these years. Thus, for aerospace industry, much of the profit is not acquired from the sale of the aircraft, but from the maintenance of them throughout the life span. The cost of MRO activities in its pure nature is very significant and around 10% in all cost drivers.

This study mainly focused on developing a system dynamics model for Turkish Airline MRO Department MRO operations. There are several system dynamics studies in the literature focused on airline operations but the MRO operations are almost neglected in them. To the best of author(s) knowledge, this is the first system dynamics study focusing on the interactions among MRO Department and other airline operations.

The developed system dynamics model presented valuable opportunities to test various MRO operations workload and aircraft fleet expansion policies in the modeling virtual world. The model can easily be used as a learning laboratory by changing various parameters and testing different policies. Such a trial is presented in the study by changing MRO operation work load (pessimistic, normal and optimistic) and by adopting different aircraft fleet expansion policies.

It is found that MRO operations have direct impact on the available number of airworthy aircrafts and the fleet seat capacity. The airline companies have to take into account the MRO operations needs of the existing and new aircrafts to sustain a profitable airline fleet.

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CLAIM FOR ORIGINALITY

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It is found that MRO operations have direct impact on the available number of airworthy aircrafts and the fleet seat capacity. The airline companies have to take into account the MRO operations needs of the existing and new aircrafts to sustain a profitable airline fleet. The most important and challenging factor is to decide on the number of MRO operations staff to employ as the variability of MRO operations work load is stochastically very high. After setting up a certain degree of confidence level, this number can be decided based on simulation results. It is also inevitable to waste the some portion of this MRO operations staff. The human resource waste can be thought as an insurance during heavy MRO operations and might also be leased to give service to third party airlines during light MRO work load of own airline.

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Assoc.Prof.Dr. Serol BULKAN

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ABBREVIATIONS

ACR	: Airport Charge Reduction
aka	: Also Known As
AMRP	: Aircraft Maintenance Routing Problem
ASC	: Airline Schedule Control
CAA	: Civil Aviation Authority
CLD	: Casual Loop Diagram
CSP	: Crew Scheduling Problem
DES	: Discrete Event Simulation
FAA	: Federal Aviation Administration
FDI	: Foreign Direct Investment
FTR	: Fuel Tax Reduction
GDP	: Gross Domestic Product
GUI	: Graphical User Interfaces
IATA	: International Air Transport Association
LFG	: Load Factor Guarantee
LRU	: Line Replaceable Units
MAE	: Mean Absolute Error
MAPE	: Mean Absolute Percent Error
MEL	: Minimum Equipment List
MIT	: Massachusetts Institute of Technology
MPD	: Maintenance Planning Documents/Database
MRB	: Maintenance Review Board
MRO	: Maintenance Repair and Overhaul
MSE	: Mean Square Error
MSG-3	: Maintenance Steering Group-3
O&S	: Operations and Support
OEM	: Original Equipment Manufacturers
OLS	: Ordinary Least Squares
PAX	: Passengers
PSS	: Product Service System

RMSE : Root Mean Square Error

SAT : Subsidies for Air Ticket

SD : System Dynamics

TTIA : Taiwan Taoyuan International Airport

VE-OPS : Virtual Environment for Operations and support Process Simulation

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1. INTRODUCTION

Turkish Airlines (THY) carried approximately 10.4 million passengers in 2003 and 50 million passengers in 2013 (THY, 2015a). As seen, in the last decade, the increase in airline passenger transportation is very significant. When air transportation is examined in Turkey, it can be seen that Turkish Airlines is the most dominant airline company in the industry. It expanded both domestic and international destinations especially in the last decade and reached up to 241 (199 international and 42 domestic) different flight destinations worldwide by the end of 2013 (THY, 2015b). Compared with the other local airlines, it has the highest amount of market share and the market share of other local small airlines can be ignored for the time being.

It can clearly be seen that Turkish Airlines tries to become a worldwide airline carrier brand and ordered approximately 200 brand new aircrafts to incorporate its fleet. The expansion of the airline fleet will have impacts in airline operations including, but not limited to, flight scheduling, fleet assignment, aircraft routing, crew scheduling, manpower planning, revenue management, fuel management systems, airline irregular operations, gate assignment, aircraft boarding strategy, scheduling and maintenance, repair and overhaul (MRO) (Bazargan, 2010).

When airline operations examined in the literature, unfortunately, there is almost no contemporary study that focus on the relations between MRO activities and other airline operations. So, this study aimed to fill this gap in literature by using very limited available data about Turkish Technic, which is the MRO department of Turkish Airlines. The publicized data is very limited and like other airlines, Turkish Airlines also prefers to keep its data as private.

It can be seen that there is strong positive correlation between flight safety and efficient MRO activities. There has been a huge effort in order to make the flying safe by the cooperation of the governments and aircraft manufacturers and, in 2010, the IATA (International Air Transport Association) announced that air transportation is safe. They have declared this by the fact that there was only one accident for every 1.6 million flights in that year. This is an utmost objective that every transportation sector dreams to reach (Sahay, 2012).

The idea of flying naturally and psychologically brings lots of concerns and this must be handled with care by maintaining a good level of safety, and sustaining well established, complicated and disciplined set of procedures. This approach initiates the term “airworthiness”, which is defined as the fitness for fly. An aircraft is considered as airworthy only if legal aircraft operator who is in charge of the safety and fitness for flight of the aircraft clearly approves it to fly. This approval is done with an Airworthiness Certificate (Sahay, 2012).

The Flight Operation Department, which is responsible for the planning of the routing and for scheduling of flights, of the commercial flights always want to keep the aircrafts flying, either by carrying passengers or cargos. On the contrary, the Engineering Department, whose job is to maintain the aircraft safe and serviceable, wants to hold the aircraft in the maintenance facility as much as needed. Even though the objectives of the both party seem opposite, it is a nightmare for Engineering Department that an aircraft is staying on the ground unscheduled. Of course, engineers also would like to see the aircrafts flying, provided that they are airworthy while doing so (Sahay, 2012).

Aircraft maintenance is unique in its characteristics and rather different than the other type of sectors such as rail and sea transportation, as it is done when aircraft loses its airworthiness. This may be urgently or in the planned future time. The immediate or unscheduled activities must be handled urgently to save the revenue. On the other hand, scheduled maintenance event is based on many different factors and it is a continuous and planned process throughout the lifecycle of the aircraft so as to keep up the airworthiness (Sahay, 2012). In other words, aircraft maintenance is a continuous process that tries to increase the degrading performance or abilities of the aircraft to its designed-in level perfection (Kinnison, 2004).

The availability of a vehicle strongly depends on both maintenance and logistics support. The logistics usually contains the management and transportation of spare parts and components for Maintenance Repair and Overhaul (MRO) needs (Iwata & Mavris, 2013).

MRO activity needs usually arose by, firstly, aircraft routine inspection, minor services and checks carried out on the aircraft at predefined intervals, secondly, scheduled

maintenance consists of replacement of the life-limited items, planned overhauls and special inspections, and thirdly, unscheduled maintenances caused by inspections, pilot reports and failures (Duffuaa & Andijani, 1999).

MRO activities hold an important place in airline operation costs. The most outstanding cost drivers of the airline operations are shown at Table 1.1. (Merkert, 2010)(Von Beuningen, 2014). The direct cost portion of airline maintenance activities when compared to other drivers seems very significant. On the other hand, the effects of bad handled maintenance activities on the other operations will surely cause more costs.

Table 1.1. Typical Airline Cost Drivers (Von Beuningen, 2014)

COST DRIVERS	% of total airline costs
Flying expenses (incl. wages, fuel, airport, insurance & en-route charges)	~40%
Maintenance and overhaul	~10%
Aircraft depreciation	~6%
Station and ground costs	~16%
Passenger services (catering, in-flight entertainment)	~8%
Ticketing, sales and promotion	~8%
General administration	~6%

So, it is a vital issue to understand the interactions of MRO activities with the other airline operations. This study will reveal those interactions and model the Turkish Technic MRO operations by using the system dynamics modeling methodology as a case study.

The remainder of the study is organized as follows. Chapter 2 presents background information about aircraft maintenance process and system dynamics methodology. Chapter 3 summarizes important studies in the literature that are executed in the field of both aircraft maintenance and system dynamics models in airline and maintenance activities. Chapter 4 describes the development of System Dynamics based model for the Turkish Technic MRO department as a case study. Chapter 5 highlights the results of the simulation scenario runs, debates about the results and discusses the applications of this research for managers. Finally, Chapter 6 discusses the conclusions and further offers suggestions to enhance the model.

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2. BACKGROUND

This sections presents information about the aircraft maintenance process and the system dynamics methodology to form a base to understand the airline MRO operations and system dynamics methodology. The interested researchers who already have enough knowledge in these subjects can skip to read this section. The first sub-section gives information about aircraft maintenance process while the second sub-section explains the overall structure of system dynamics methodology.

2.1. Aircraft Maintenance Process

There is a main difference between general plant and machinery maintenance and aircraft maintenance in that aircraft maintenance is compulsory and observed by regularity authorities such as the Federal Aviation Administration (FAA) and Civil Aviation Authority (CAA). Thus, aircraft maintenance has well-established and standardized processes (Sahay, 2012).

When a new type aircraft is going to be produced or designed, a MRB (Maintenance Review Board) is established including regulatory authorities, OEM (Original Equipment Manufacturers) and other related members deemed to add value. The regulatory compliance is the core of aircraft maintenance and it is prescriptive. They put forward maintenance tasks universally and those tasks are applied exactly in the same manner across the world, that is, it doesn't matter where the aircraft is it gets the same maintenance (Sahay, 2012).

The Maintenance Steering Group-3 (MSG-3) recommends the aircraft maintenance processes to be executed as task oriented, whose all tasks are defined from start to end. Thus, an engineer executes the tasks that are defined and approved previously. This is the indication of completeness of the task description in the MSG-3 procedure. Those tasks are usually grouped in three; airframe system tasks, structural items tasks and zonal tasks. All of them make up fourteen core unique tasks which are used while executing maintenance. The combination or permutations of these tasks make up the building bricks of the maintenance processes and a few of these processes put forwards

the maintenance programs. As a matter of fact, these tasks guide to create a number of maintenance activities that end up with work packages (Sahay, 2012).

MSG-3 is a kind of process for an aircraft type and is used by the MRB to identify and classify maintenance activities for the aircraft parts that might end up with failure. That is, in order to keep up the airworthiness, the specification of aircraft components to be maintained and the means of doing so are determined. Then, the result of this work is used by OEMs to produce maintenance plans for the operators. These plans are defined as MPD (Maintenance Planning Documents/Database). By using the MPD, the operators create their own maintenance plans and then, schedule their maintenance operations. Hence, those approved maintenance programs are used to maintain the airworthiness of the aircrafts (Sahay, 2012).

Nearly, all aircraft maintenance programs are naturally preventive in view of airworthiness. You can not apply the classic “break-fix” approach in the aviation industry as there is no roll-back mechanism when an aircraft has fallen out of the sky.

In aviation industry, there are two kinds of aircraft maintenance modes, namely, scheduled and unscheduled maintenance. In a holistic maintenance world, unscheduled maintenance events presumably should not occur but, in the real world, that’s not the case. It is a common phenomenon to see occurring of the unscheduled maintenance events, which are usually a subset of scheduled maintenance events and so handled in the same manner (Sahay, 2012).

In practice, following the aircraft’s mission flight, the aircraft has been inspected routinely to spot the degrading components. Afterwards, corrective or unscheduled maintenance is performed to fix the broken parts during the flight, and then, any forthcoming scheduled maintenance is applied to the aircraft. The scheduled maintenance is mainly rooted on a measurable metric such as flight time, distance traveled or number of operational cycles. Upon completion of the maintenance activities, turnaround activities such as refueling are performed before the next flight. In parallel to these activities, logistics activities also continuously take place, that is, transport, repair, and replenish broken and spare parts (Iwata & Mavris, 2013).

2.1.1. Maintenance Objectives

The core objective of the aircraft maintenance is to make the aircraft fly as long as possible. Based on this guidance, MSG-3 has defined four quantitative objectives for aircraft scheduled maintenance; firstly, making sure of the fulfillment of the natural safety and reliability levels of the aircraft, secondly, restoring or rolling back the safety and reliability of the aircraft to its natural level when degradation or failure occurred, thirdly, delivering the gathered information for the items whose natural reliability inadequate for redesign, fourthly, achieving these goals, involving maintenance and failure costs, at a minimum total cost (Sahay, 2012). Moreover, Viles et al. (2007) adds reduction of the repair time to the maintenance objective (Viles, et al., 2007).

In some cases, these objectives may be incapable of correcting the deficiencies to its natural safety and reliability level. Scheduled maintenance only aims to inhibit the deterioration of such required natural level; moreover, it's inherently preventive. If the result of the maintenance is deemed to be unacceptable, design modification is essential for improvement. Design modification is often the responsibility of the manufacturer and the commercial aviation organization almost never takes on this responsibility. The measures of main maintenance objectives are “dispatch reliability” and “turnaround time” and can be summed up as “prompt delivery of airworthy aircraft to the airline reliably, consistently and cost effectively” (Sahay, 2012) (Zhu, et al., 2012).

From engineers stand point, the first three objectives are related, entirely assessable and usually reachable but on the other hand, the fourth objective creates the biggest anxiety among them. There is no silver bullet solution for the optimized minimization of the total maintenance costs; moreover, MSG-3 only defines general statements to manage the costs. This is left as an internal issue for the operators by the regulatory authorities (Sahay, 2012).

2.1.2. Aircraft Maintenance Strategies

Aircraft maintenance, in theory, is usually handled in the hanger according to the plan. There is almost no maintenance activity on board when the aircraft in the air, flying due to the security or the nature of jobs to be done. The maintenance objectives are achieved by adopting the strategies mandated by the regulatory authority (Sahay, 2012).

The first strategy is the redundancy, which can be defined as building more than one system or component considering criticality by design, in case of failure, airworthiness still managed by those spare ones. The second strategy is to use of line replaceable units (LRU). These are modular components that can be easily and quickly replaced with new ones when the symptoms of the faults are observed. Thus, there is no need to repair the faulty component on the spot by LRU engineer, rather, it must be replaced with the serviceable one and faulty one must be sent to the workshop for repair. The third strategy is the minimum equipment list (MEL) that is used to list the serviceable equipments maintaining the airworthiness of the aircraft. So, not all the components of an aircraft need to be serviceable to fly safely. As a matter of fact, maintenance organization heavily benefit from this list to plan and perform the defect corrections in a much more concentrated manner (Sahay, 2012).

2.2. Systems Dynamics Overview

The applications of feedback control theory in simulation model of organizations was initially introduced and demonstrated by Jay Forrester of Massachusetts Institute of Technology (MIT) in the 1950-1960s (Forrester, 1958). Forrester's this study indicates the birth of professional field known as "system dynamics" (Maani & Cavana, 2007). Since then, by the contribution of various researchers, this powerful methodology enriched and developed based on system theory, information science, organizational theory, control theory, tactical decision-making, cybernetics and military games (Abbas & Bell, 1994)(Shepherd, 2014). System dynamics has been applied to many different fields, disciplines and subjects such as defense, urban and regional development, business, banking, industry, economics, finance, manufacturing, biology, education, health, medicine, dentistry, engineering, forestry, fishery, energy, environment, transportation, psychology and various others (Abbas & Bell, 1994). It offers a new way of thinking that can be defined as a whole system approach. It takes care of invisible complexity, ambiguity and mental models (Maani & Cavana, 2007). It provides effective tools and techniques to better understand, study, visualize, and analyze the large-scale complex dynamic feedback systems (Dyson & Chang, 2005) (Maani & Cavana, 2007)(Zhao, et al., 2011).

System dynamics reminds us of the definition of the 'system'. A system can be thought as 'a collection of parts that interact with one another as a whole'. It is not the sum of its parts; rather, it is the product of its interconnections, which means inherently handling of nonlinear relationships (Maani & Cavana, 2007). Moreover, it can be defined as 'a community of connected entities' which highlights the 'connectedness' among the components comprising the system of interest (Sherwood, 2002). So, a system interacts as a whole and when any part of it is missing, it loses its function totally or partially (Maani & Cavana, 2007).

System dynamics, aka system thinking, is a scientific method to understand 'change and complexity' by the study of dynamic cause and effect over time (Maani & Cavana, 2007). It is important to comprehend the connections and relations among the investigated system and its parts. Abbas and Bell (1994) have defined system dynamics as 'a rigorous method for qualitative description, exploration and analysis of complex systems in terms of their processes, information flows, organizational structure; delays, policies, decision rules and strategies.' Systems thinking brings forth four types of thinking:

- forest thinking - the capability to see the big picture and understand the relations and interactions among component parts (Maani & Cavana, 2007),
- dynamic thinking - comprehension of the fact that world is not static and things change by the time (Maani & Cavana, 2007),
- operational thinking - mapping of the relationships that capture interactions, interconnections, the sequence and flow of activities, and the rules of the game. It shows the physics of operations that portray how things work and affect each other, in other words, it reveals what is linked to what and how changes in one part of the system might influence to others and turn back (Morecroft, 2007)(Gharajedaghi, 2011)(Maani & Cavana, 2007),

- Closed-loop thinking – realization of the fact that cause and effect are nonlinear in nature and, most of the time, the effect can impact the cause (Maani & Cavana, 2007).

Systems thinking presents a tool (language) to investigate and make deductions about the complexity and dynamic cause and effect. This language is visual and diagram based, has its special rules (syntax), translates perceptions into explicit pictures, clarifies the closed interdependencies (Maani & Cavana, 2007).

Systems thinking offers the modeling and learning technologies to unfold the system behavior and structure. Moreover, these tools help to discover the relationships and the interconnections among components of a system and show how a change in the system affects the whole system and its elements over time. These tools mainly consist of the causal loop maps, stock and flow models and computer simulation software (Maani & Cavana, 2007). This approach is commonly used in a hierarchical manner to investigate the interaction of system and policies across time and space (Shepherd, 2014).

2.2.1. System Dynamics Principles

System Dynamics (SD) used analogously with Systems Thinking in the literature and its main principles can be summarized as the following (Anderson & Johnson, 1997)(Maani & Cavana, 2007).

2.2.1.1. The Big Picture

‘The big picture’ principle is the art of seeing the forest and the trees, and whole may mean more than the sum of its components. What we see may be related to the bigger forces and interactions (Maani & Cavana, 2007).

2.2.1.2. Short and Long Term

‘Short and long term’ principle implies that short term precautions may degrade the long term outcomes, in such a situation; one has to take necessary measures to save the day. While an organization facing ‘life threatening’ situation, very rapid interventions may be inevitable to overcome it. However, if this ‘crisis management’ situation lasts

for a long time then, the effects of adopting this policy persistently can endanger the life of the organization in the long run (Maani & Cavana, 2007).

2.2.1.3. Soft Indicators

‘Soft indicators’ principle states that conventional performance measures such as key performance indicator, critical success factor and balanced score card can only reveal part of the story. Other than these, there are additional invisible powerful potential factors which affect the behavior and performance of organizations. They consist of such things like morale, burnout, commitment, loyalty, confidence, genuine care and capacity for learning. These can be considered as the ‘measures’ of the inner soundness and spirit of an organization (Maani & Cavana, 2007).

2.2.1.4. System as a Cause

‘System as a cause’ principle states that most of the problems faced in an organization are created internally not only because of the unintended results of our decisions and actions but also because of our mental models such as beliefs, values, and assumptions. As a result, many people or organization considers themselves as ‘victims’ and not the problem introducers. To cope with this, organizations must continuously interrogate and make their mental models, habits, values and assumptions public, and moreover, encourage the employees to express themselves with creative dialogues with relation to the forces that form and impact the performance (Maani & Cavana, 2007).

2.2.1.5. Time and Space

‘Time and Space’ principle implies that cause and effect in many cases do not interact closely in time and space due to not only the time delays but also the hidden connection triggered by the chain effects of the actions between cause and effect. Therefore inherently, today’s problems are often related to, and most of the time, result of the yesterday’s solutions (Maani & Cavana, 2007).

Frequently, action and response, effort and outcome, decision and result are far apart and as a result, their cause and effect relationships are unnoticeable. In the long run, consequences of the cause and effect relationships can be observed clearly (Maani & Cavana, 2007).

2.2.1.6. Cause versus Symptom

‘Cause versus symptom’ principle assert that, in our daily life, people can define an event as a problem, but in reality, it is the symptom of that problem. Therefore, most of the precautionary measures do not handle the real root that originates the problem, instead just the symptoms. So, in order to solve a problem, the causes of that problem must be understood well. All the causes of the problem must be identified and addressed to reach a long lasting solution (Maani & Cavana, 2007).

2.2.1.7. Either-or Thinking

‘Either-or thinking’ suggests that most of the problems or decisions do not have a binary (either-or) option, on the contrary, they have a potential with multiple outcomes. Instead of simple cause-effect relationship, there may be multiple causes and effects for a given problem or solution (Maani & Cavana, 2007).

2.2.2. Casual Loop Diagram

SD methodology connects the qualitative and quantitative models. Casual loop diagram (CLD) is a qualitative model that puts forward the dynamic hypotheses about a system and used before the development of stock and flow quantitative model. It can be thought as a ‘mental model’ that overlays the abstraction, interrelationships, connectedness of the system by setting out casual links among the different stakeholders and components of the system. Thus, it reveals the ideas about how people think a system works, and then, takes care of the frontiers to implement a proposed policy (Shepherd, 2014). CLD publicizes not only clear but also masked interconnections briefly and visually (Morecroft, 2007).

CLD, a qualitative model, usually offers good opportunities to capture the system input requirements and behavior from the relevant system users. Model development process usually starts with overall system sketches that portray the characteristics of the system and need not to be so detailed. On the contrary, for the sake of parsimony(Liehr, et al., 2001, p. 320), it is sometimes preferable to use the simple models, which capture the system like a cartoon. A cartoon is not drawn in detail but it depicts the most

outstanding features. The same approach is valid for the development of the CLD (Maani & Cavana, 2007).

Each casual loop has a story about how the effects keep up with the cause in the end. During the model evolution, CLD connects the entities as cause-effect relationships, thus feedback loops become apparent. These loops are called either balancing (negative) or reinforcing (positive) loops. Balancing loop acts as a countermeasure to the change, therefore an increase in one element forces a decrease in another element within this loop. Reinforcing loop augments flows in such a way that an increase in one element causes an increase in another one. Balancing and reinforcing loops within a system lead to a dynamic equilibrium altogether (Shepherd, 2014).

Arcs are used to show the casual relationships or connection between the system elements. Relation is read from ‘tail’ to ‘head’ of the arc, that is, ‘tail’ component affects the ‘head’ component. The augmentation of the relation is denoted with + (increase) / – (decrease) sign around the arc. If the two variables move up and down together, the arc sign is + (or ‘s’ meaning same). When the two variables move in opposite directions, the arc sign is - (or ‘o’ meaning opposite). In case of complex loops, whole loop polarity is calculated by total number of negative links, in that an even number means reinforcing loop while an odd number means balancing loop. Loop polarity is usually depicted as +/- signs or R/B letters inside the loop with a circular arrow which shows the direction of the flow (Maani & Cavana, 2007)(Shepherd, 2014).

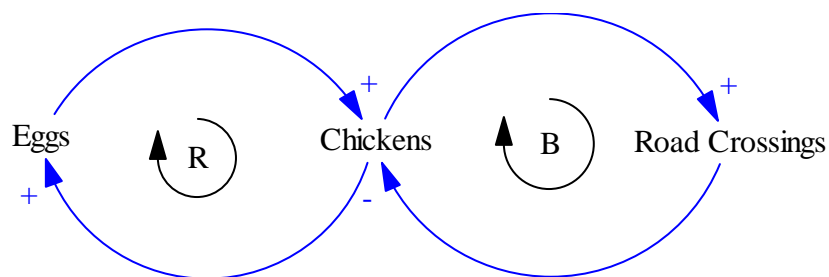


Figure 2.1. Dynamic Interactions in a CLD (Sterman, 2000)

A simple example of casual loop diagram is shown in Figure 2.1 (Sterman, 2000). If there is at least one rooster, chickens will produce eggs that are suitable for breeding. As number of eggs increase, this will in turn lead to produce more chickens. The more eggs

means, the more chickens and vice versa. When this reinforcing loop operates its own, both chickens and eggs will increase exponentially without any limit. In case of chickens and road crossings balancing loop, the more chickens mean the more road crossings, which results with chicken deaths. These deaths, considering this loop isolated from the system, will cause the chickens to become extinct eventually. When both loops interact concurrently over time according to some certain rates, they will eventually reach to a dynamic equilibrium (Shepherd, 2014)(Sterman, 2000).

2.2.3. Stock and Flow Diagram

Even though qualitative models, in our case CLD, are fruitful to describe the structure and dynamic behavior of the system, most of the managers are keen on seeing the quantitative results. For this purpose, stock and flow diagrams are used in the SD methodology. Stocks are accumulations — both physical and non-physical — depicted as rectangle boxes to keep the content. The computer symbol of the ‘stock’ is depicted in Figure 2.2. They may be entities such as money, inventory, aircraft, population, maintainers, knowledge, data, sales, births, deaths. Conditions of the stocks always exist in the system, even though the flows reach to a halt state (Maani & Cavana, 2007) (Shepherd, 2014).



Figure 2.2. Stock Representation

Flows (rates) are depicted as pipes with valves which regulate the rate of flow and represent activities or actions in a stock that carry quantities into or out of a stock instantly or over a period of time. They are generally the outputs of decisions made by decision makers or of exogenous forces that not in control of decision makers. The computer symbol of the ‘flow’ is depicted in Figure 2.3. The direction of the pipes may be into the stocks, increasing the content of the stock at flow rate, or out of stock, decreasing the content of the stock at flow rate (Rehan, et al., 2011)(Shepherd, 2014).



Figure 2.3. Flow Representation

Mathematically the relationship between stocks and flows can be formulized using the following integral form (Sterman, 2000);

$$\text{Stock}(t) = \int_{t_0}^t [\text{Inflow}(s) - \text{Outflow}(s)] ds + \text{Stock}(t_0) \quad (2.1)$$

where t_0 is the initial time, t is the current time, $\text{Stock}(t_0)$ is the initial value of the stock, $\text{Inflow}(s)$ and $\text{Outflow}(s)$ are flow rates into and out of a stock at any time s between the initial time t_0 and current time t . $\text{Inflow}(s)$ and $\text{Outflow}(s)$ have the units of $\text{Stock}(t)$ divided by time (Rehan, et al., 2011).

Converters or auxiliary variables are intermediate variables that include constants, built-in functions, graphical and behavioral relationships. The benefit of using converters is that they help to break complicated equations into simple equations and relations, which is much easier to comprehend. The computer symbol of the ‘converter’ is depicted in Figure 2.4 (Maani & Cavana, 2007)(Rehan, et al., 2011).

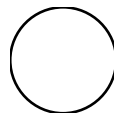


Figure 2.4. Converter Representation

Connectors are arrows to set up relationships among different variables of the model and transports information as inputs for decisions or actions (Rehan, et al., 2011). Clouds represent the sources and sinks for the flows. The computer symbol of the ‘connector’, ‘source’, and ‘sink’ is depicted in Figure 2.5. A source represents the entry point, originated from outside of the boundary of the model, to the system; while sinks represent the exit points of the system to outside world. Sources and sinks are assumed to have infinite capacity and can never constrain the flows they support (Sterman, 2000)(Rehan, et al., 2011).

There are also information and physical time lags, say delays, in system dynamics modeling which can be defined as the elapsed time passed between the start and end of an action (Abbas & Bell, 1994).

As stocks and flows are connected with other stock and flows, a sequence of non-linear differential equations are constructed which form the structure and behavior of the system. Developing a model that captures the most outstanding features and behaviors of the system is a challenging subject and seems more like an art. It is good idea to develop the models with the stakeholders, but in case of lack of this opportunity, start with the simple concept models that portrays the endogenous behavior of the system, which is sometimes advantageous to use small, simple models over the more complex and detailed ones (Ghaffarzadegan, et al., 2011)(Shepherd, 2014).

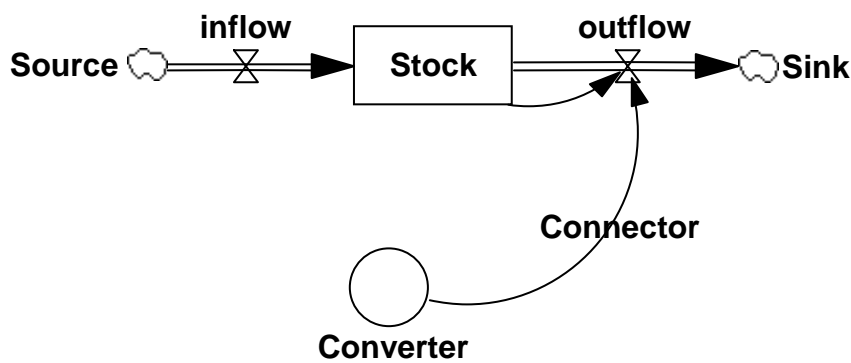


Figure 2.5. Sample Stock and Flow Diagram in Vensim Software

2.2.4. SD Methodology

Abbas and Bell (1994) proposed a system dynamics modeling whose steps are identification of a problem, definition of a problem, variable generation and model development, system verbalization, system conceptualization, model formulation, computer programming, simulation and system analysis. For the detailed explanation about these steps see (Abbas & Bell, 1994).

Barlas (1996) defined the major steps used in a typical system dynamics study as problem identification, model conceptualization (construction of a conceptual model), model formulation (construction of a formal model), model analysis and validation, policy analysis and design and implementation (Barlas, 1996).

Table 2.1. Systems Thinking and Modeling Process (Maani & Cavana, 2007)

PHASES	STEPS
Problem Structuring	<ol style="list-style-type: none"> 1. Identify problems or issues of concern to the management and main stakeholders 2. Collect preliminary information and data 3. Conduct group sessions for creative problem structuring
Casual loop modeling	<ol style="list-style-type: none"> 1. Identify main variables 2. Prepare behavior over time graphs (reference mode) 3. Develop casual loop diagrams (influence diagrams) 4. Analyze loop behavior over time 5. Identify system archetypes 6. Identify key leverage points 7. Develop intervention strategies
Dynamic modeling	<ol style="list-style-type: none"> 1. Develop a system map or rich picture 2. Define variable types and construct stock-flow diagrams 3. Collect detailed information and data 4. Develop a simulation model 5. Simulate steady-state/stability conditions 6. Reproduce reference mode behavior (base case) 7. Validate the model 8. Perform sensitivity analysis 9. Design and analyze policies 10. Develop and test strategies
Scenario planning and modeling	<ol style="list-style-type: none"> 1. Plan general scope of scenarios 2. Identify key drivers of change and keynote uncertainties 3. Construct forced and learning scenarios 4. Simulate scenarios with the model 5. Evaluate robustness of the policies and strategies
Implementation and organizational learning	<ol style="list-style-type: none"> 1. Prepare a report and presentation to the management team 2. Communicate results and insights of proposed intervention to stakeholders 3. Develop a microworld and learning lab based on the simulation model 4. Use learning lab to examine mental models and facilitate learning in the organization

Maani and Cavana (2007) have defined the phases of systems thinking and modeling methodology as seen in Figure 2.6 and Table 2.1.

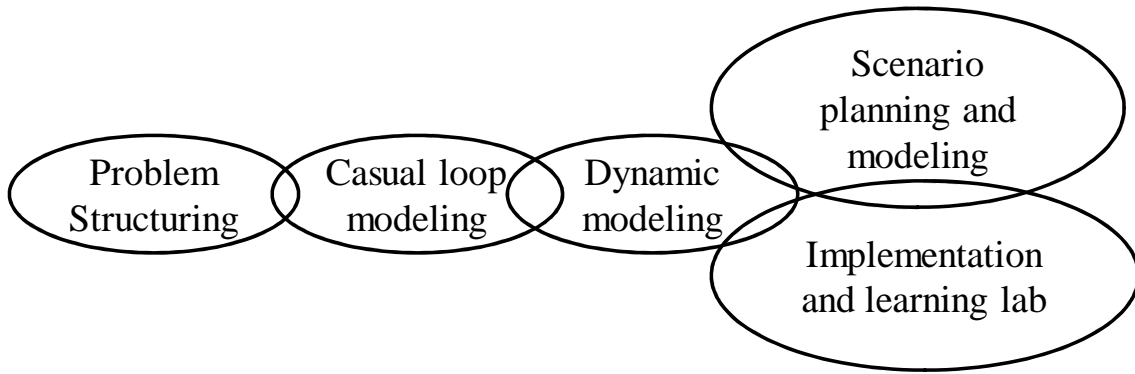


Figure 2.6. Phases of the Systems Thinking and Modeling Methodology (Maani & Cavana, 2007)

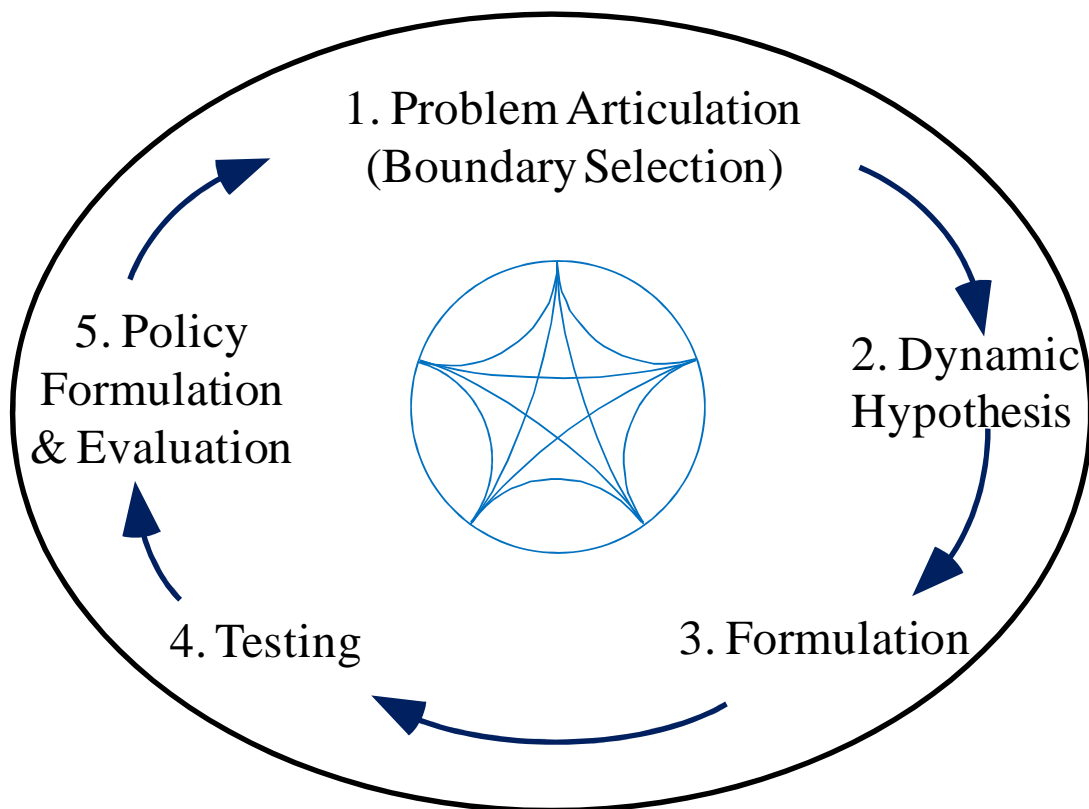


Figure 2.7. The Iterative Modeling Process from (Sterman, 2000)

Even though there are many other studies that propose methodology for system dynamics, Sterman's (2000) well-established system dynamics modeling process has been selected as basis. He provides a very detailed explanation for the modeling steps and defines different model validation types in detail. The modeling process consists of five iterative stages: problem articulation, formulation of dynamic hypothesis,

formulation of a simulation model, testing, and policy design and evaluation as seen in Figure 2.7.

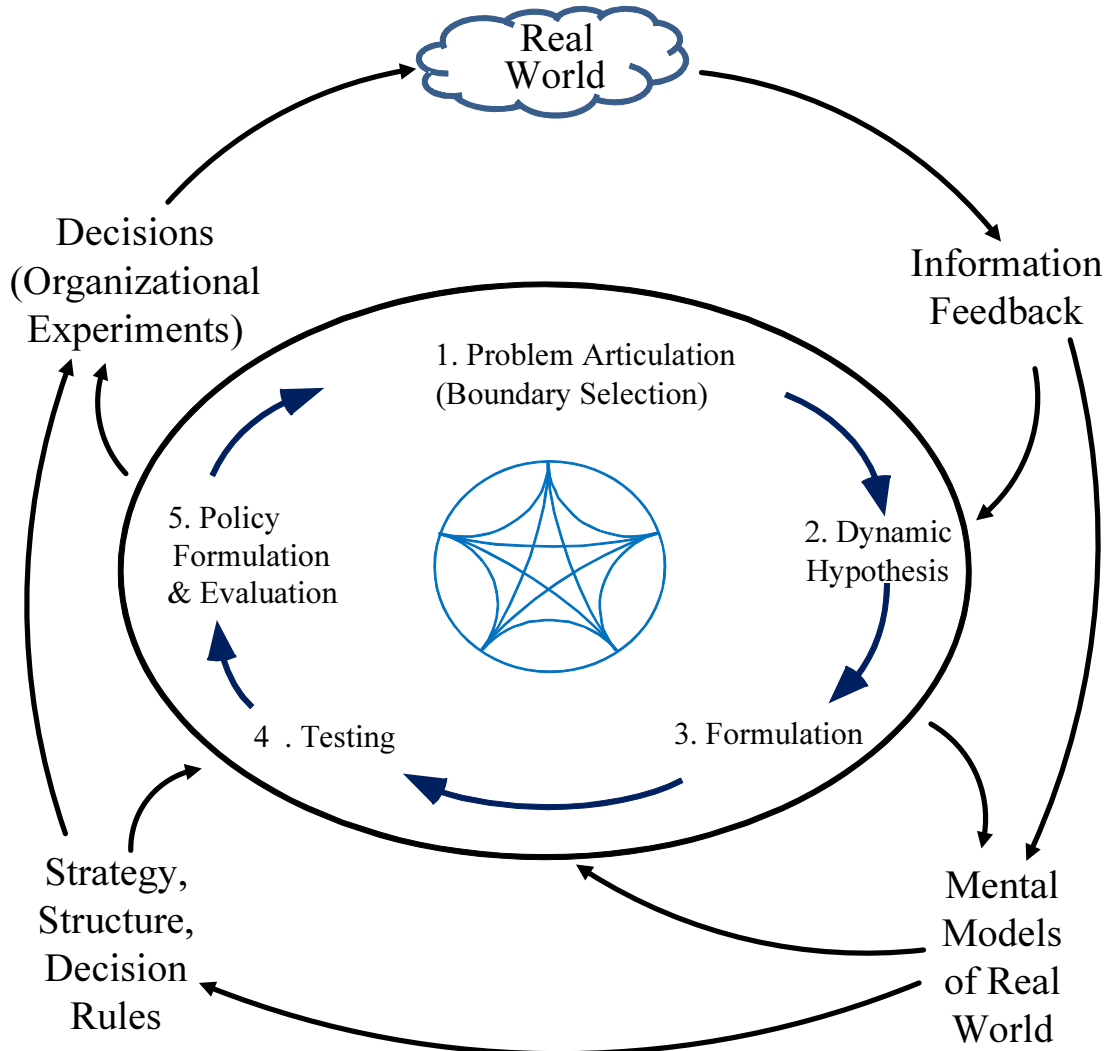


Figure 2.8. The Dynamics of System Dynamics Modeling (Sterman, 2000)

Modeling is not a sequential process and is nonlinear in nature that involves feedbacks. Thus, during modeling, it is needed to question, test and refine the proposed model iteratively to reach the desired modeling state. The initial step of modeling is to define the boundary and scope of the problem but, the feedbacks coming from what is learned during modeling can also alter the recognized definition and the purpose of problem. The iteration can be initiated from any step to any other step. This is represented by the

interconnections in the center of the diagram (see Figure 2.7). These iterations are executed many times until the model matures (Sterman, 2000).

Simulation models are affected by both our mental models and the information gained from the real world. Strategies, structures, and decision rules applied in the real world can be adopted and tested in the virtual world of the model. The new strategies, decisions and policies tested in the model can feed back to the real world to alter our mental models and guide to adopt new strategies, structures, and decision rules in the real world. The implemented new policies in the real world bring the new effects in the system which again leads to new insights and better improvements in the formal and the mental models. So this interaction cycle continuously takes place between the real world and the virtual world as seen in Figure 2.8 (Sterman, 2000).

2.2.5. Overview of the Modeling Process

2.2.5.1. Problem Articulation: The Importance of Purpose

The most important issue in the modeling process is the identification of the problem that imposes the definition of a clear purpose for the model. A well-defined model purpose gives opportunities for questioning whether the model is useful to unfold the concerns of the clients (Sterman, 2000).

The model should focus on the problematic area rather than try to mimic the whole system under investigation. In view of this fact, a useful model must attempt to address the problem area and must avoid modeling the entire system in detail. A model is usually designed to unfold a problem that is specific to a policy issue. Thus, the success of a model is based on simplifying the reality to a degree that the representation of it can be understood. In this perspective, it becomes crucial what features of a system to include and to ignore to accomplish the purpose during model building phase. On the other hand, when an attempt is initiated to construct a holistic model, this turns out to be a never ending effort. So there is a trade-off while keeping and omitting the features of the system. The purpose of the model behaves as a logical knife while cutting out the unwanted system features in the model. In summary, an analyst must model a problem rather than a system (Sterman, 2000).

System dynamics modelers should prepare a set of graphs and other descriptive data that shows evaluation of the problem over time. This work is used as a reference mode while evaluating the development of the model. Time horizon, variables and concepts must be identified to better understand the problem at hand. Behavior over time graphs must be prepared for those which deemed to be most important. There are delays in cause and effect relations in the system dynamics models. That is why; the time horizon should be extended far enough not only back in history but also into the future to reflect the effects of those relations (Sterman, 2000).

2.2.5.2. Formulating a Dynamic Hypothesis

After specifying an adequate time horizon, modeler must put forward a theory, called a dynamic hypothesis, to reveal the characteristics of the problematic behavior. This hypothesis is dynamic as it needs to establish an explanation about the dynamics that define the problem in terms of fundamental feedback and stock and flow structure of the system. It is a hypothesis since it is subject to the evolution rooted from what is being learned from both the modeling and the real world. Moreover, other than the changes applied to the hypothesis, it may even been rejected during this maturation period. That is why, a dynamic hypothesis is an ongoing theory that try to capture how the problem arose (Sterman, 2000).

While seeking for the hypothesis, note that it is important to capture all the sources of the problem which will probably lead to different theories about the causes of it. In literature, there are various types of elicitation techniques and diagramming tools to dig into the theories about the roots of the problem. System dynamics focuses on the interactions of variables and agents captured in the model and looks for endogenous explanations among them, which are endogenous behaviors. Endogenous means “arising from within”, while exogenous means “arising from without”. The number of exogenous variables should be kept as small as possible, as what caused them to change may not be explained at all. They must be investigated in detail to check whether they introduce any important feedbacks to the endogenous variables and included in the model if so (Sterman, 2000).

What is the level of detail in a good model? As mentioned before, it depends on the purpose of the model but, a broad model boundary that captures the important feedback structures is preferable to a model whose individual component specifications are modeled with a lot of detail (Sterman, 2000).

System dynamics supports modelers to define the boundary of the models and to represents the casual structure with the help of various tools such as model boundary tools, subsystem diagrams, casual loop diagrams and stock and flow maps (Sterman, 2000).

Model boundary chart summarizes the key variables captured in the model according to their scopes as endogenous, exogenous and excluded. Subsystem diagram portrays the overall structure of a system by splitting the system into the sub-systems or components and by linking these components with the flows such as material, money, goods, information and so on. These diagrams show information boundary and the level of aggregation in the virtual world representation. Thus, information flows among the endogenous and exogenous variables are conveyed in these diagrams (Sterman, 2000).

Model boundary chart and subsystem diagram sketch the boundary and architecture of the model but unable to clarify the relationships among variables. Casual loop diagrams are very useful and flexible to explain the feedback relationships of a system. These relationships can be defined as casual links which have arrows from cause to effect. Stock and flow diagrams highlight the fundamental physical structure. Policy structure diagrams reveal the information flow as input to a certain decision rule. The concentration is given to the information cues that deemed to affect the decision making about governing the rates of the flow in the system. They focus on the casual structure and time delays relating with a specific decision instead of the feedback structure of the overall system (Sterman, 2000).

2.2.5.3. Formulating a Simulation Model

After the development of the first dynamic hypothesis, model boundary, and conceptual model, it is necessary to test them. There is always a chance to test them directly when collecting data or experimenting with the real system. On the other hand, the conceptual model is likely too complex to clearly see its dynamic implications. That is why, in

most of the cases, experiments can be conducted in virtual world. So, a transition is needed from a conceptual model to a concrete complete model whose equations, parameters, and initial conditions are formally defined (Sterman, 2000).

During formalization phase, some valuable insights about system characteristic can be gained even before the simulation. Moreover, formulation helps not only to clarify vague concepts but also to eliminate contradictions that is overlooked or undiscussed during conceptual phase. A lot of test can be conducted to grasp the flaws in formulation of the problem and likewise, how you understand the system advances (Sterman, 2000).

2.2.5.4. Model Testing

The testing usually starts with the first written equation. The equation must have dimensional consistency. The behavior of the simulated model must mimic the behavior of real system. But this just cannot be downgraded to resemblance of historic behavior. Each variable in the model must adequately represent a significant concept in the real world. The sensitivity of model behavior and policy proposals should be evaluated by considering uncertainty on structural as well as parametric assumptions (Sterman, 2000).

Another important test is to use the extreme conditions which normally never seen in the real system. There are also other tests whose sole purpose is to capture the flaws in the model (Sterman, 2000).

2.2.5.5. Policy Design and Evaluation

After reaching to a satisfactory confidence in the structure and behavior of the model, a certain type of policy can be designed and analyzed for improvement of the system. Policy design is not the same with changing just the value of parameters. It encompasses the formation of completely new strategies, structures, and decision rules. As the feedback structure usually describes its dynamics, improvement of the policy usually introduces changes to the structure of the most dominant feedback loops by redesigning the stock and flow structure, getting rid of time delays, altering the flow and

quality of the information at key nodes, or sometimes regenerating the decision processes of players in the system (Sterman, 2000).

The model performance should be tested under various ranges of alternative scenarios. It is also very important to investigate the soundness of the policies and their sensitivity to ambiguities in model parameters and structure. The interactions among different scenarios should be checked. As the real systems are nonlinear in nature, influences of combination of scenarios are usually not the sum of them. There are also interferences and synergies among the policies (Sterman, 2000).

3. LITERATURE REVIEW

This section mainly focuses on the studies executed in the area of aircraft maintenance and airline operations as well as system dynamics studies performed in this area.

3.1. Maintenance Related Studies

Mathaisel (1996) offered an ASC (Airline Schedule Control) environment which integrates the different scheduling tools with standardized Graphical User Interfaces (GUI), standardized data structures, and standardized hardware platforms. ASC was implemented to improve the operational efficiency in the command and control of real-time aircraft movements. The aim was to coherently yield communications means among all the related departments such as operations control, crew management, maintenance, airport management, marketing by a common interface to the schedule planning system, crew planning and management systems, the maintenance scheduling system, as well as other existing mainframe computer systems (Mathaisel, 1996).

Duffuaa and Andijani (1999) came up with a simulation framework for Saudi Arabian Airlines consisting of the modules planning and scheduling, supply, quality control, maintenance organization and performance measures. This framework mainly integrates the maintenance activities and operations (Duffuaa & Andijani, 1999).

Moudani and Mora-Camino (2000) suggests an algorithm that aims to solve the joint problem of fleet assignment problem and embedded maintenance schedule by mixing a dynamic programming approach, to cope with the fleet assignment problem, and a heuristic technique, to solve the embedded maintenance schedule problem (Moudani & Mora-Camino, 2000).

CIMdata (CIMdata, 2002) defined three major considerations in any product lifecycle: product definition, production definition, operational support. Product definition contains information about how the product is designed, manufactured, operated or used, serviced, and then retired. From a manufacturer's point of view, the lifecycle of a product comprises five phases: imagination, definition, realization, support, and retirement (Dutta & Wolowicz, 2005)(Lee, et al., 2008)(Stark, 2011). Manufacturer is responsible for the maintenance of the product in the support (or use) phase. Following

the retirement of the product, it is either disposed or recycled. Adoption of the PLM to the design phase of aircrafts produced spectacular results. Still, the potential benefits of PLM adoption to MRO activities have not been well understood and the use of PLM in the support phase, starting from the product design, is not common in the aviation industry (Lee, et al., 2008). Virtual Environment for Operations and support Process Simulation (VE-OPS), based on discrete event simulation, is another initial effort to include the maintenance and logistics design and analysis into the overall design process of a vehicle system (Iwata & Mavris, 2013).

In theory, PLM supplies trustworthy and precise feedbacks among enterprise partners at various lifecycle stages of a product. These feedbacks can be used to optimize inventory levels and enhance the efficiency of scheduled or unscheduled maintenance by reducing the non-value add tasks (Lee, et al., 2008).

Lee et al. (2008) highlights the chances, advantages and caveats of implementing today's product lifecycle management (PLM) in the aircraft maintenance, repair and overhaul (MRO) industry. When the aerospace industry is examined, the life span of aircrafts is usually around 30 years (Airbus, 1999). So, aircrafts need lots of maintenance services in these years. Thus, for aerospace industry, much of the profit is not acquired from the sale of the aircraft, but from the maintenance of them throughout the life span (Lee, et al., 2008) (Dutta & Wolowicz, 2005). Majority of the vehicle life cycle cost is caused by the operations and support (maintenance and logistics) activities (Iwata & Mavris, 2013).

Wu (2008) proposed a data collection framework to enhance the robustness of turnaround operations and take advantage of real-time monitoring of the collected data. He used the mobile computing devices and wireless network technology as infrastructure for the suggested framework. They showed a couple of benefits of real-time observation of the data. Firstly, operation controllers can identify and take precautionary measures to correct the cumbersome activities by recording the start and end time of the activities. Secondly, the root causes of the delays can be assessed by making use of the collected data, moreover, better ground handling services can be achieved. Lastly, the time stamps at the stored data can be used to improve the airline schedule optimization algorithms (Wu, 2008).

Zhu et al. (2012) proposed a web-based product service system (PSS) framework to integrate the product development process with the related maintenance and service process, and extended the responsibilities of the manufacturers throughout the life cycle of the aircraft. They made an initial effort to show usage of proposed methodology in the aerospace industry as a decision support tool for MRO services (Zhu, et al., 2012).

Gargiulo et al. (2013) defined an algorithm based on the combination of a dynamic programming strategy and an agent-oriented approach to plan the aeronautical maintenance activities. They benefit from the parallel computation characteristic of the multi-agent strategy that allows distributed computing. Thus, a better load-balance and coordination mechanism, in turn, guarantees the actions of multiple agents guide to a global solution (Gargiulo, et al., 2013).

McLaughlin and Durazo-Cardenas (2013) adopted the cellular manufacturing concepts to the MRO operations and reported the productivity improvements and less lead times. Six businesses practicing MRO operations were evaluated the extent and benefits of adoption of manufacturing techniques to MRO operations. They all observed benefits in turn-around time and operational performance but, also emphasized the difficulties arising from the variability of input conditions which affects labor, material, equipment, knowledge requirements and the scheduling of post-assessment operations (McLaughlin & Durazo-Cardenas, 2013).

Iwata and Mavris (2013) developed a Discrete Event Simulation (DES) environment, named Virtual Environment for Operations and support Process Simulation (VE-OPS), to examine operations and support (O&S) activities of aerospace vehicles using an object-oriented programming language. These O&S activities contain the maintenance process to repair and replace broken components and the logistics system which restock the spares in the inventory. For the sustainment of the vehicle, VE-OPS provides capability to exploit the various scenarios based on different concepts and to make sensitivity tests. Moreover, stochastic events can be introduced into it, and as a result, interactions can be observed (Iwata & Mavris, 2013).

Marais (2013) states that focusing on the contribution of the maintenance activities to the value of the system rather than thinking the maintenance activities as cost drivers

will help us to produce optimal system wide maintenance policies. In view of this fact, she puts forward a general repair optimization problem to identify the value-optimal actions for a system condition at any time by employing a semi-Markov decision process, discounted cash flow techniques, and dynamic programming. The factors that affect the maintenance policy such as operating cost and revenue, system failure characteristics, repair and replacement costs, and the planning time horizon, are explained (Marais, 2013).

Díaz-Ramírez et al. (2014) proposed an algorithm consists of the combination of the integer mathematical programming model and a heuristic to solve the aircraft maintenance routing problem (AMRP) and the crew scheduling problem (CSP) in sequential and integrated fashions for airlines having a single fleet with a single maintenance and crew base. In this model, they try to assure that each aircraft gets its maintenance needs according to the flight schedules (Díaz-Ramírez, et al., 2014).

Zuidberg (2014) proposes a parametric analysis approach to estimate the effects of airline operating costs. He presented results of a random effect and fixed effects estimation for 2007-2010. The fixed effects techniques are used to control the airline-specific effects that do not or barely vary over time such as business strategy, image and region. Then, in order to estimate the effects of time invariant variables on the fixed effect term, he used an ordinary least squares (OLS) regression. In this research, the airline characteristics that play a role on the average operating costs per aircraft movement are investigated. The results showed the existence of economies of density, economies of load factor, economies of aircraft utilization and economies of aircraft size, on other hand, enough evidence aren't found for economies of scale, economies of stage length or economies of fleet commonality. It is interestingly found in the study that full freighter airlines, member airlines of worldwide alliance and airlines operating a multi-hub system produced much more average operating costs per aircraft movement. The regression result showed more average operating costs per aircraft movement for the airlines of consisting of brand new aircrafts because, ownership costs (depreciation and leasing costs) of new aircraft overrides the increasing maintenance costs of old aircraft. The airlines that dominate the hubs or bases usually have greater operating costs per aircraft movement due to the lack of the significant competitive pressure,

which results in charging expensive ticket prices and guiding restricted concentration on cost savings. It is also emphasized that this study has a shortfall as it only considers the costs, not both costs and revenues, while profitability is calculated based on both. Low cost always doesn't mean profitability for companies (Zuidberg, 2014).

3.2. System Dynamics Studies in Airline and MRO Activities

Abbas and Bell (1994) have summarized the twelve advantages of using system dynamics (SD) that might contribute to the transportation sector as seen at Table 3.1. As summarized in this table, there are significant advantages to use system dynamics methodology in transportation sector.

Table 3.1. System Dynamics Contribution to Transportation Modeling (Abbas & Bell, 1994)

No	ADVANTAGES
1.	SD furnishes a logical, systematic and detailed representation of complex large-scale systems, such as transportation systems. In SD, representation entails modeling (in terms of structure and policies) and simulation (analyzing and testing) of systems.
2.	Conventional transport modeling methodologies are oriented toward achieving a supply/ demand equilibrium. This requires assumptions that are difficult to satisfy in reality. In SD the dynamic, feedback interactions between supply and demand in transportation systems are explicitly accounted for.
3.	In most transportation studies, the land-use, socioeconomic and demographic forecasts are obtained using separate modeling techniques. These are then used as external inputs into transportation models. This may ultimately result in inconsistencies and incompatibilities in the modeling procedures, leading to inaccuracies of results. Transportation planning lacks the comprehensive, holistic view in which feedbacks between transport and other sectors are considered. This ignores the totality of impacts that transportation systems may have on their environments. SD methodology can provide a common framework through which transport and other related sectors can be incorporated and modeled.
4.	In SD models, data are mainly required to define reference modes, estimate parameters, determine other parts of system structure and determine the model's initial values. However, data may be collected later to fill gaps in constructed models and, in fact, an SD transport model can act as a means for assessing the appropriate data needed for future enhancement of the model.

5.	The methodological advantages of SD are such that the results of an SD transport model are mainly reached through the dynamic, causal feedback interactions of the structural components of the model, as well as through empirically based formulations. In contrast, in conventional statistical regression models results are reached purely through empirically based formulations. The structural elements of an SD transport model interact to produce a dynamic behavior of the transport system. Nonlinearities and time delays can be accommodated explicitly.
6.	SD methodology can be used as a basis for constructing and testing a priori hypothetical models of different transportation problems. It can incorporate alternative policy or structural assumptions, input data or empirical parameters. SD strives to incorporate relationships of subjective (behavioral) phenomena rather than ignore and exclude these relationships.
7.	SD provides a rich and coherent conceptual working environment, which brings order and makes the maximum use of the modeler's mental and modeling agility. This can be achieved by formulating transport models, as much as possible, in clear, transparent and diagrammatic forms as well as in an algebraic form. Understanding gained through building an SD transport model and manipulating that model can be as useful as that gained from long association with the transport system in the real world. SD conceptualization procedures can also provide a common platform for communication and understanding between the various parties that have interest in a transport system.
8.	SD can assist in developing experimental transport tools. These tools are meant to provide flexibility in design and analysis and to enable tests to be made over a wide variety of transport policy options and scenarios: The models can be used as training tools to help familiarize transport personnel with the different transportation problems.
9.	Through SD simulation, the short-term and long-term behavior of a transport system is traced. This can provide insight into the dynamic nature of the transport problem and allow for timely adjustments to be made, if required.
10.	Low cost, transparency, transferability and ease of updating are characteristics that support the application of SD to model transportation problems.
11.	Building transport models using the SD approach can help in identifying controls in the transport system being modeled. These controls are meant to guide the efforts of policy-makers regarding which parameters and/or structures of a transport system could be managed and controlled to produce better performance of the system.
12.	According to (Willumsen, 1990), "a transport model is not simply a set of mathematical instructions used to simulate and forecast travel demand, it implicitly structures the way in which transport problems are viewed and understood and the type of solutions that are considered feasible and testable." SD methodology can provide a foundation for structuring thoughts and building a better understanding of complex transportation systems and their underlying problems.

Liehr et al. (2001) conducted a research to analyze the basic, cycle-generating behavior of the Lufthansa German Airlines and identify alternative business strategies for

effective 'cycle-management'. Airlines cyclical behavior observed not only after the introduction of gross domestic product (GDP) fluctuations in main major industrialized regions of the earth (North America, Europe, Japan) but also after the deregulation of the market in the USA (Liehr, et al., 2001).

There are various factors that influence customers to select a certain airline but, the most important ones are the schedule and price. As punctuality is very important for business travelers, they prefer the airlines that keep up with tight schedules regardless of the airfare. On the other hand, the biggest cost of a flight caused by the direct operating costs and a single ticket price is very low in this big picture, that is, the marginal cost for each passenger is low. Therefore, airline carriers certainly want to fill the aircrafts with as many passengers as possible which results in low frequency flights to the destinations. In view of these facts, aerospace capacity planning and flight scheduling are the most prominent factors that come forward amongst others. Unless the typical dynamics of these factors are identified and managed properly, the aerospace industry will be affected by a discount in stock prices, relative to other sectors. This state guides to the obligation of handling business cycles successfully (Liehr, et al., 2001). The period of this kind of cycle in airline industry is approximately eight to ten years, which is consistent with machine investment cycles and are regarded as the traditional economic cycle (Schumpeter, 1939, p. 161) (Liehr, et al., 2001).

There is a common belief among airline managers that the cycles are caused as a response to the fluctuations in the development of the GDP and this is out of control of the industry. As a result, it is beyond the capability of the industry to smooth the oscillations and to minimize the damaging effects of these cycles on the profitability of industry. However, Liehr et al. (2001) has demonstrated with robust evidence that the cycles of the airline industry are endogenous. They showed several critical points that have important effects on a balancing loop in their SD model. This balancing loop has two delays which lead to oscillations around the target seat load factor. One of these delays is the long lead-time of manufacturers to deliver the new aircrafts and the other one is the recognition of the delay in case of overcapacity (surplus) passengers. The lag between aircraft order and deliveries is around 18-24 months before new aircrafts join to expand the passenger capacity. Speeding up the old aircraft retirement may be an

option to lessen the overcapacity. Overcapacity (excess seats) gets bigger in parallel with the integration of new aircrafts to the fleet, meaning new seats; on the other hand, declines with acquiring more passengers. As a result, enlarged overcapacity lessens the aircraft order sizes according to the acceptable surplus absorption limits (Liehr, et al., 2001).

Airlines normally struggle to increase their revenues by using seat capacity at its maximum extent. However, due to the lead times for new seat capacity and lagged identification of the over capacity, the system begins to fluctuate around the target seat factor. Simulation results showed that oscillations are observed in the system independent of the ongoing demands for flights. An extension of the model that includes a price management to regulate the demand revealed that the long-term cycles cannot be eliminated in the system; rather management policies only affect the amplitude and period of the waves. Furthermore, cycles in the airline industry are generally induced by the endogenous factors while exogenous factors just affect the amplitude of the cycles. Thus, exogenous factors are clearly not guilty for the cause of the cycles (Liehr, et al., 2001).

Some leverage points are proposed to stabilize the system. One of them is the regulation of capacity-demand balance by leasing or retiring the overcapacity. Alliance is another option for this purpose. Shifting the overcapacity from low demand to high demand regions is used heavily after the liberalization and deregulation of the airline market and decreased the overcapacity to a certain degree. To keep old aircrafts as spare capacity in case of capacity need and retire them at low cost during demand downturns is another leverage point (Liehr, et al., 2001).

Bivona and Montemaggiore (2010) used system dynamics to investigate the alternative maintenance policies for two city bus companies as a case study in Italy. Following the reduction of public funds at the local municipalities, the budget for the public services is lessened, one of which is the bus transportation. As a restructuring strategy to this budget cut, bus fleet preventive maintenance cost is reduced. However, this short-sighted solution has lead to an unexpected financial downturn in the medium-long term. Decision makers can propose policies which add high benefits to a company subsystem but, on the other hand, such policies can endanger the whole company performance and

harm the long-term sustainable growth. So, in order to sustain the profitability of the company as a whole, managers should not just look into the maintenance policies effectiveness but they must investigate the casual interrelations among the subsystems that affect each other (Bivona & Montemaggiore, 2010).

From this point of view, Bivona and Montemaggiore (2010) constructed a system dynamic model that includes maintenance related production, finance, asset management and human resources. There is a coupled relationship between maintenance activities and finance. Maintenance activities produce costs, in another word; you need financial resources to sustain asset availability. This reduces the operating profit of the company. However, when this relationship between maintenance activities and finance deeply investigated, there are some delayed and counterintuitive phenomena. When more budgets were allocated for maintenance activities, this could increase maintenance activities, which means higher asset availability. As a result, we observe better maintenance production performance, happy customers and, more efficient and improved financial outcomes in medium-long term (Bivona & Montemaggiore, 2010).

When it comes to financial influence on the maintenance, maintenance activities are usually carried out on the grounds of financial priorities and not the actual maintenance needs. This policy always looks for the reduction of the financial costs, which has a reflection in maintenance site as fewer budgets. This may improve the financial state in short term, but in the long run, maintenance production could decline sharply because of the unanticipated outcomes. Ignoring the preventive maintenance activities will eventually increase the asset failure probability, which in turn may end up with a boost in asset breakdowns. Thus, these breakdowns will increase the maintenance department workload which is hard to cope with. So this vicious cycle degrades maintenance efficiency and produces poor financial results (Bivona & Montemaggiore, 2010).

Asset management methodology also has impact on maintenance activities in that the brand mix of several assets, the average age of components and the embedded level of technology are dominant factors. That is why these factors have to be considered during the asset procurement period. The rejuvenation of the fleet may introduce high investments in the short term, but in the long run, because of the lower asset failures, it

could cause less maintenance activities and better financial results. Moreover, maintenance activities also has chance to affect the asset management policies. The capability loss of maintenance department to repair the broken assets lessens the life span of the assets. This will introduce additional investments more frequently to renew the fleet (Bivona & Montemaggiore, 2010).

The other division that interacts with the maintenance activities is the human resources function. The capacity and capability of maintenance is mainly based on available human resources and the equipment. The number of people, level of knowledge and skill as a whole impacts the productivity of the maintenance department. Overtime or high workload to increase maintenance capacity causes to lower the productivity because of factors such as fatigue and attention disorder. Moreover this policy in the long run, due to the greater personnel turnover, may elevate rookies' ratio over experts, which in turn could result in reduction in maintenance capacity and more training costs (Bivona & Montemaggiore, 2010).

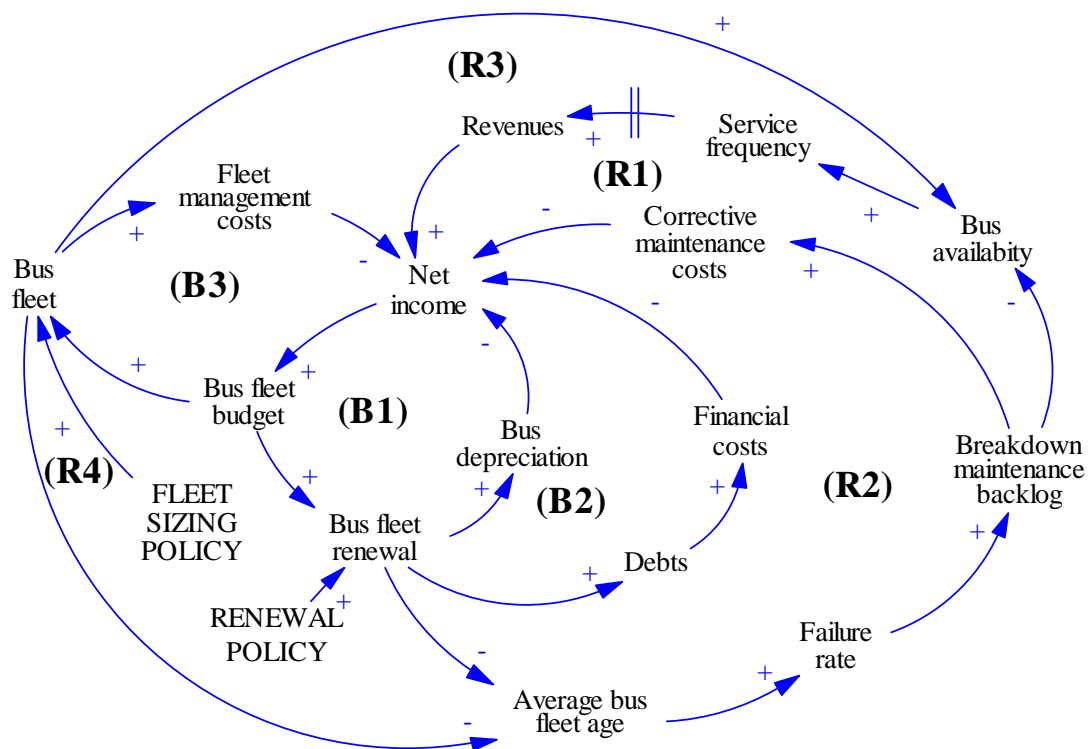


Figure 3.1. Fleet Management Area Casual Loop Diagram from (Bivona & Montemaggiore, 2010)

While analyzing the cause-effect relationships, Bivona and Montemaggiore (2010) have focused on four areas; fleet management (asset sector), maintenance scheduling (maintenance sector), maintenance capacity management (maintenance and human resource sectors) and service management (production sector). The fleet management area casual loop diagram can be seen in Figure 3.1.

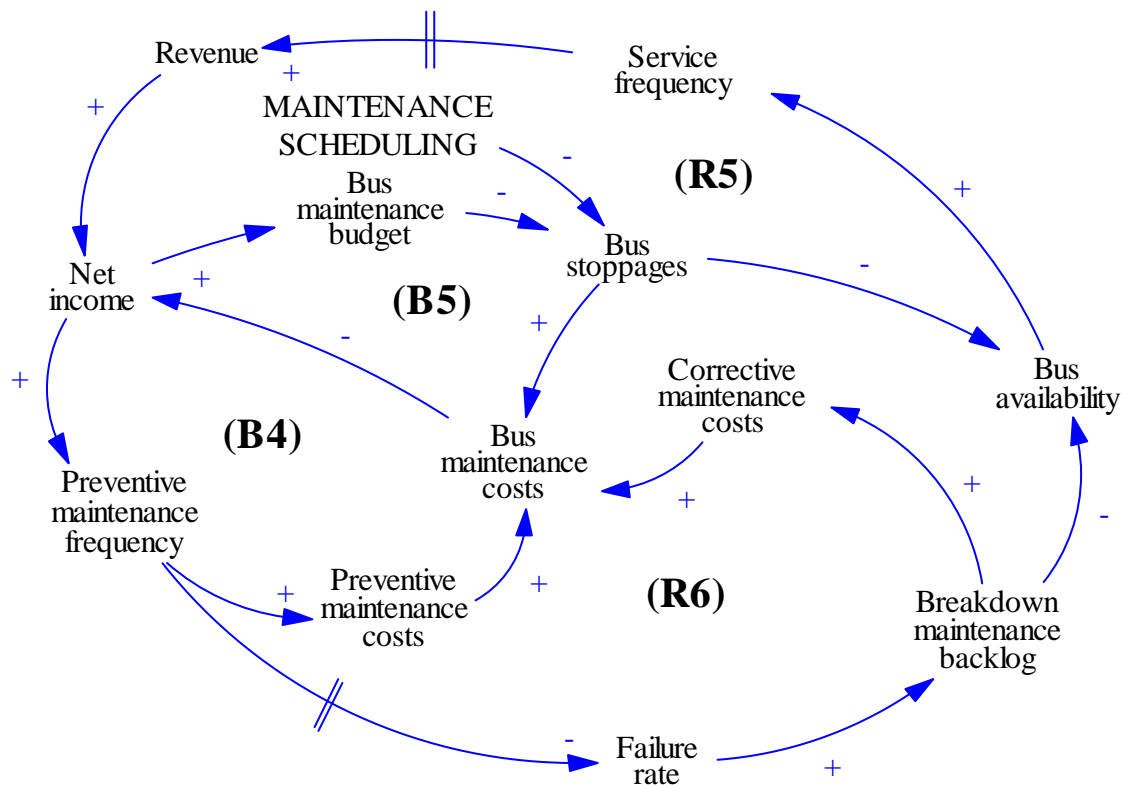


Figure 3.2. Maintenance Scheduling Casual Loop Diagram from (Bivona & Montemaggiore, 2010)

In fleet management area, they took into account fleet renewal and fleet sizing policies. The rejuvenation of fleet decreases the average bus fleet age. This in turn introduces lower failure rates that have positive impact on the maintenance production and net income. However, renewal policy means higher bus depreciation, so lower profits, and higher financial costs due to buying new buses. Fleet sizing policy results with higher bus availability which in turn leads to higher service frequency, and after a late recognized delay, greater customer satisfaction. As a result, the number of passengers, revenues, net income and budget to renew the fleet expected to increase. Similarly with

renewal policy, fleet sizing policy also decreases the average bus fleet age, which means less maintenance activities (Bivona & Montemaggiore, 2010).

In maintenance scheduling area (see Figure 3.2.), the number of buses to go to the preventive and the corrective maintenance tasks must be decided. The critical issue is to select how many buses are needed to meet the daily service needs. If you restrain more buses for maintenance tasks, then these buses will not serve, so revenue will decrease. Conversely, a reduction in bus stoppages will cause to increase available buses and the service frequency. This helps to produce better service levels by generating high revenue and net income. Additional resources can be invested to bus maintenance budget to decrease the bus stoppages. It is worth to invest to preventive maintenance as it decreases the asset failure rate. When the number of bus stoppages is reduced, maintenance costs will go up, thus the net income will reduce. In case of adopting more frequent preventive maintenance, more costs would be introduced to the overall system, thus a reduction in company net income (Bivona & Montemaggiore, 2010).

For the maintenance capacity management area, four policies are identified: maintenance hiring, overtime, outsourcing, and maintainer training (see Figure 3.3.). The first three strategies seem to have positive impact on the maintenance capacity which causes to reduce the breakdown maintenance backlog and affects more bus availability, service frequency, revenue and net income. This elevated net income, in turn, can finance maintainer hiring, overtime hours, and outsourcing. On the other hand, these three strategies cause higher maintainer costs and outsourcing costs (Bivona & Montemaggiore, 2010).

Maintainers consist of rookies and experts according to work skills. The rookies have to be trained by experts to become experts for a certain amount of time. Therefore, a portion of experts work time seems to be spent to train rookies which, initially, causes to decrease the productivity of expert maintainers. In the longer run, these rookies will become experts and company will have more maintenance capacity (Bivona & Montemaggiore, 2010).

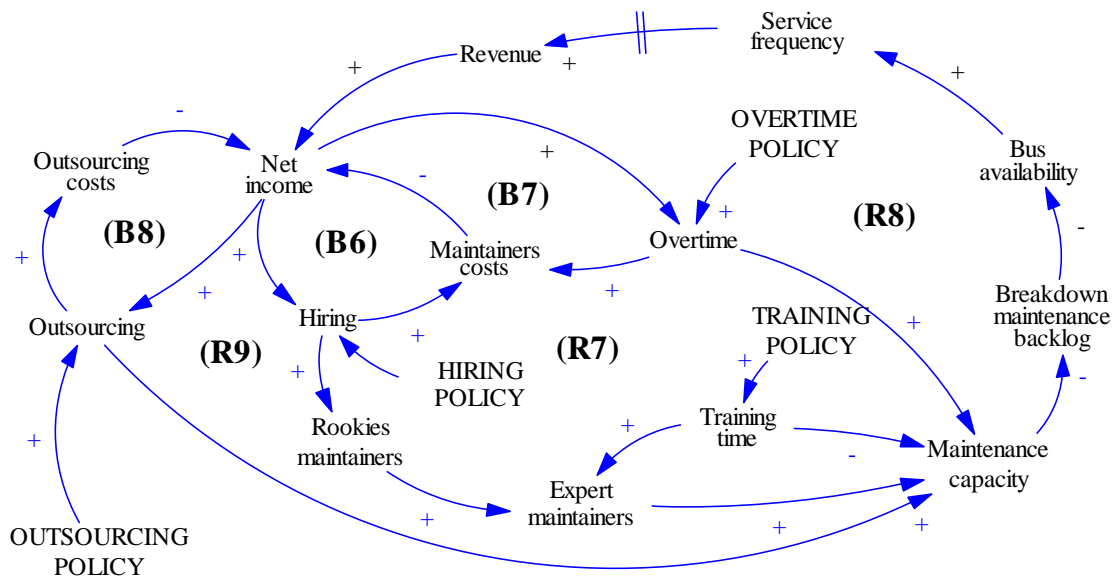


Figure 3.3. Maintenance Capacity Management Casual Loop Diagram from (Bivona & Montemaggiore, 2010)

In service management area, managers decide to redistribute the bus fleet coherently among the service lines according to the line characteristics and to requirements of the service contracts (Bivona & Montemaggiore, 2010).

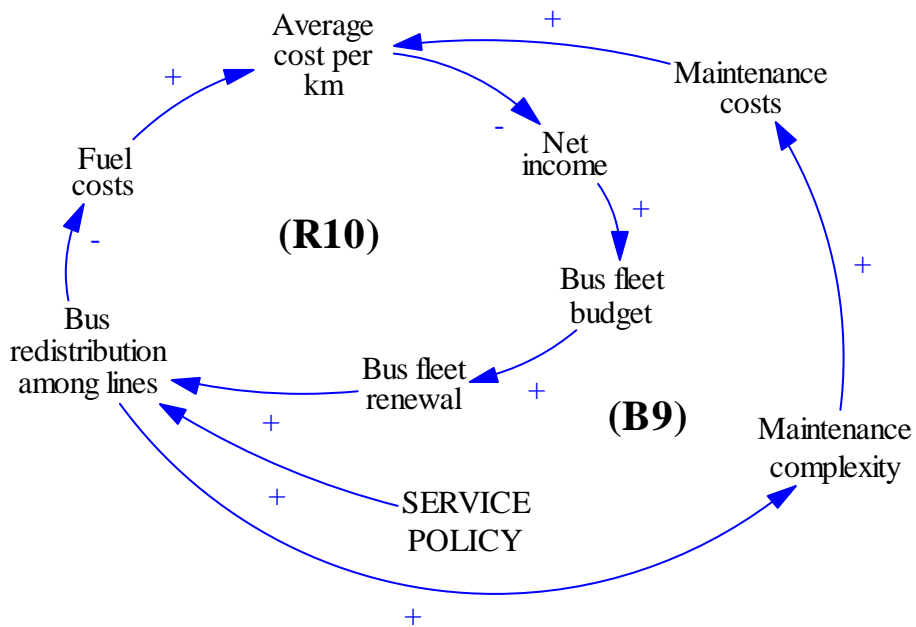


Figure 3.4. Service Management Casual Loop Diagram from (Bivona & Montemaggiore, 2010)

In scenario runs, spare busses needed to replace the broken or mothballed busses for preventive maintenance and on average 75 percent of the busses are available for daily service. For the case in study, an average 0.20 breakdowns per 1000 km observed. Outsourcing may not be selected as it raises the risks of losing not only the maintainers' skills but also the company's know-how. Additionally, contracting out the maintenance activities bring two burdens to the company: the maintainers salaries and outsourcing costs. Firing may not be an option as it would introduce the problems with unions and local laws (Bivona & Montemaggiore, 2010).

Minato and Morimoto (2011) have investigated business strategies by using system dynamics methods for Japanese regional airports which are commercially unsustainable due to the low and fluctuating demands. When airports are built in places which do not attract enough passengers, special strategies have to be employed to sustain commercial viability. These kinds of strategies can be listed as subsidizing aircraft purchases and discounted tickets by governments, reducing airport charges, reimbursing revenue losses, and sometimes assuring load factors of flights. As airport transportation consists of the airports, airlines, aircrafts, passengers, governments and communities, a systemic approach is selected to reveal the complex behaviors among these multiple stakeholders as in Figure 3.5 (Minato & Morimoto, 2011).

Minato and Morimoto (2011) have reviewed some studies about regional airport management. In these studies, it is stated that accessibility, innovation, ownership, parking and connectivity are the factors that most add value to the commercial viability. In this perspective, commercial viability is built upon both the aeronautical revenues and business revenues gained from non-aeronautical events (Minato & Morimoto, 2011).

Minato and Morimoto (2011) pinpointed airlines, airports, passengers, local governments and local communities as main stakeholders in the system. They examined six management strategies that are commonly used to sustain unprofitable regional air transportation: fuel tax reductions, airport charge reductions, subsidies for aircraft purchases, profit loss compensation, load factor guarantees and subsidies for airline tickets. These policies have to consider the global benefits for all the stakeholders. For example, fuel tax reduction (FTR) and airport charge reduction (ACR) can reduce

revenues. It also means more trading activity in airports and in the community which help to improve the local economy. As a result, improved economical prosperity usually attracts more people to live in and to do business in the region, which in turn again, creates more air passengers. Concurrently, it also elevates the LFG to a more pleasant state. SAT policy seems to create expenditures for the government but it is possible that the government eventually will get more revenues due to the overall revenue increase in the ecosystem. Thus, this policy seems to be the most efficient and effective strategy (Minato & Morimoto, 2011).

The simulation data tuned to the Noto-Haneda flights in Japan from 2003 to 2009. The results showed that ticket price subsidies, especially for visitors, in parallel with the means to improve the non-aeronautical revenue are the most contributive strategy to enable the financial sustainability of the regional airports (Minato & Morimoto, 2011).

Miller and Clarke (2007) have proposed a methodology which is the combination of system dynamics and Monte Carlo simulation to evaluate the strategic value of the air transport infrastructure as in Figure 3.6. In this study, they hypothetically try to put forward strategies to solve the congestion on the runway. Congestion directly increases the operating cost of the airlines which is usually passed on to the passengers as higher ticket prices. Once the congestion is observed, a capacity increase is needed after a period of time. That is why, the combinations of congestion threshold limit, amount of capacity to increase and the time required to increase that capacity describe the different types of capacity delivery strategies. In simulations runs, it is found that small capacity increments in short response times can yield more benefits than large capacity increments in long response times. However, short response time to raise the capacity require a priori investment. The strategy to decide when to increase the capacity can be the observation of the congestion threshold. In this simulation runs, 75% congestion threshold is considered as a triggering situation. Furthermore, Monte Carlo simulation is used to address the multiple sources of the uncertainty (Miller & Clarke, 2007).

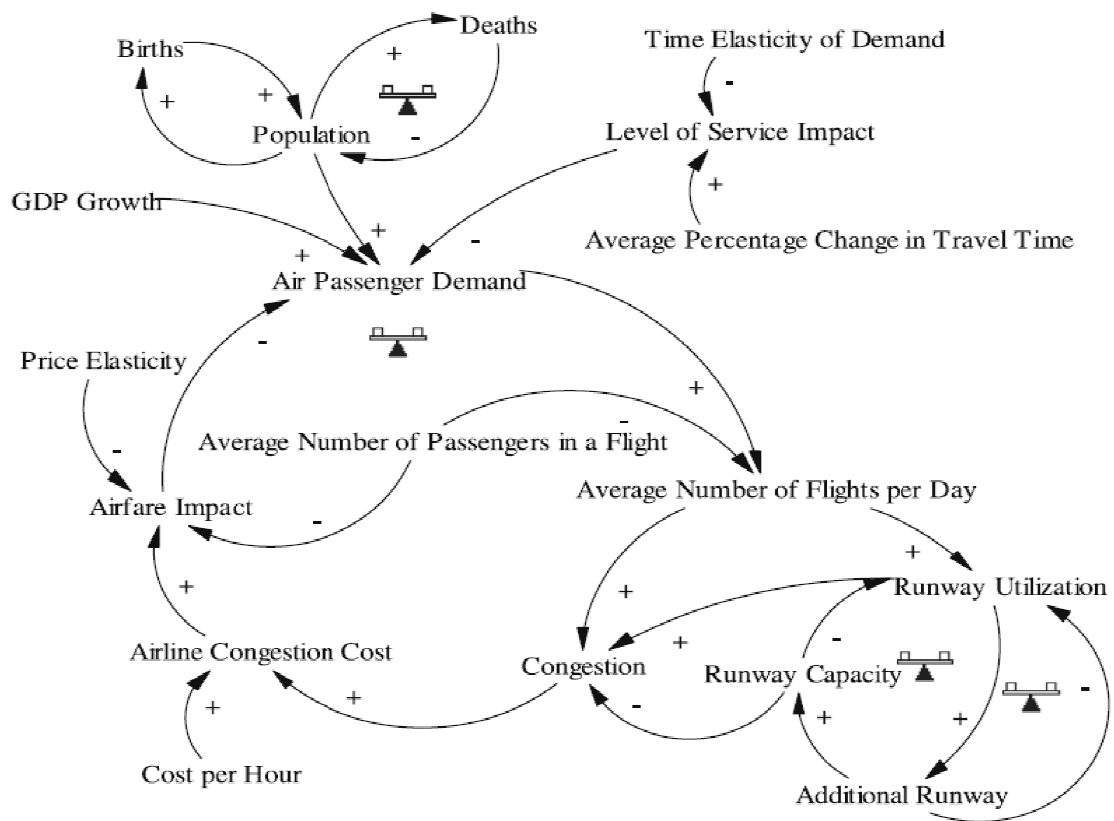


Figure 3.7. Causal Loop Diagram of Air Passenger Demand And Passenger Terminal Capacity Expansion in (Suryani, et al., 2010)

Suryani et al. (2012) extend their model to forecast air cargo demand associated with terminal capacity expansion based on scenarios that have optimistic and pessimistic economic projections. In view of this fact, it is stressed that there is a strong positive correlation with the size of the air cargo demand and trade volume and economic activity. Air cargo demand is affected by factors such as foreign direct investment (FDI), import, and transit growths but the most influential factor is the GDP growth among others as it represents the economic activity. The scenarios tested for the 20 years horizon for the Taiwan Taoyuan International Airport (TTIA) and capacity expansion will be needed after the year 2018 for optimistic scenario and after the year 2030 for pessimistic scenario (Suryani, et al., 2012).

Manataki and Zografos (2010) proposed a generic system dynamics model to assess the performance of the Athens International Airport passenger terminal based on different 'what if' demand increase and resource allocation scenarios. The model is built on the intention of being generic so as to adopt it easily to the other airports. In the model,

airport is decomposed into two hierarchical levels; first one is the functional areas and second one is the decomposition of these functional areas into the service levels. These service levels are represented by modules which are interconnected to compose the airport functional areas. At a higher level, these functional areas are also combined to form the airport terminal. In scenario run based on the of 25% increase in passenger traffic, delays are observed on the security screening areas, check-in areas and at passport control facility accompanied with level of service deterioration. The solutions of these delays are assessed by deploying additional resources to the screening points and check-in counters (Manataki & Zografos, 2010).

Steverink and Van Daalen (2011) have investigated the factors that affect the airport demand shift of passengers due to the immediate airline ticket price increase/decrease. In a more concrete sample, they try to explain the asymmetric response of the system observed when Dutch government introduced the tax to the airline ticket fares at all departing flights in The Netherlands and quitted that tax after one year. This tax policy is introduced so as to compensate the emission of CO₂ and other greenhouse gases related with the associated air travel. After the tax introduction to the ticket prices, an immediate passenger shift observed from Eindhoven International Airport, Netherland, to the airports Charleroi, Belgium, and Weeze, Germany. After the abolishment of the tax, the same sudden shift is not observed; rather a slow backshift is seen. In this study, a cognitive decision making sequence of (Erasmus, et al., 2001), which consists of the sequences of *problem recognition/pre-search stage, information search, evaluation of alternatives, choice and outcome evaluation*, is put forwarded to form the foundation of the system dynamics model. The information search can be regarded as a triangle whose corners are the preferences, alternatives and attributes. The selection of the alternatives depends on the three factors, first one is the budget and other constraints, second one is the situation of missing some alternatives (not heard of them), and third one is the discarding some of the alternatives as they are not meet the minimum requirements. In order to obtain the required information, personnel experience, word-of-mouth, and marketing (advertisement) are used as a source. To evaluate the alternatives while selecting a specific airport, a utility function is used which is the weighted combination

of the average ticket price, average arrival time to the airport and the number of the flights available at the airport (Steverink & Van Daalen, 2011).

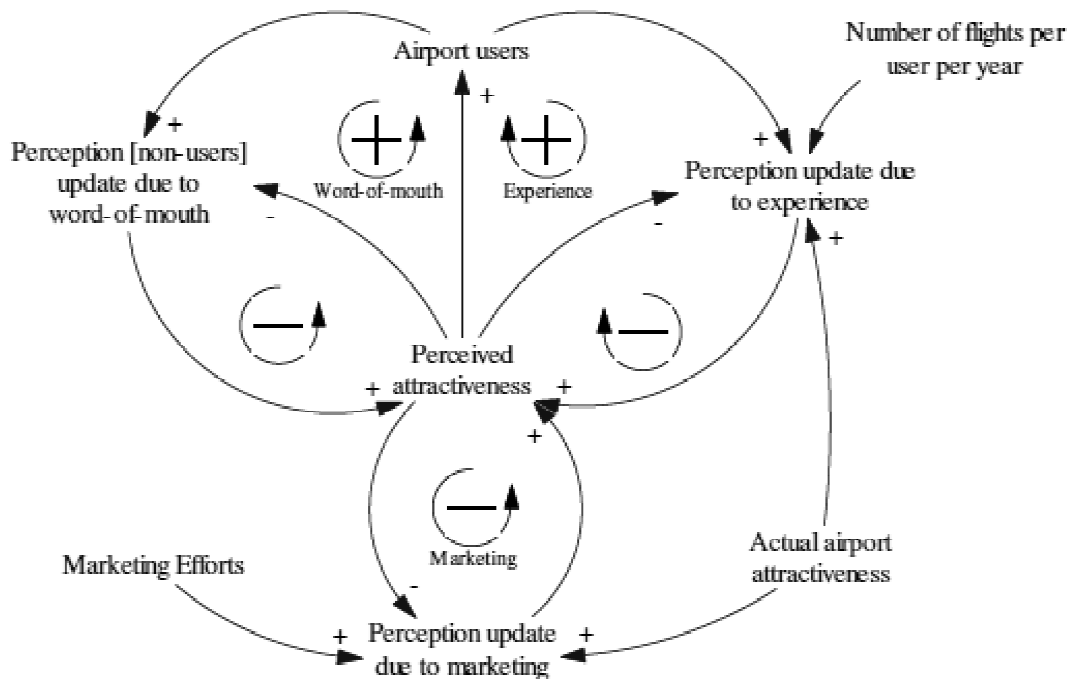


Figure 3.8. Information Acquisition in (Steverink & Van Daalen, 2011)

The information acquisition CLD of (Steverink & Van Daalen, 2011) is depicted in Figure 3.8. In system dynamics simulation, awareness of the alternatives is a key enabler to select the other competitive airports during the introduction of taxation on airline tickets. If there is a high awareness, a steep passenger shift can be observed towards the alternative airports. On the other hand, even though the taxation policy is abandoned all of a sudden, the same reverse passenger shift may not be observed due to the slow awareness of this situation. The competing airports should be ready to meet these kinds of demand shifts by supplying the additional capacity for demands and by publicizing themselves as a good alternative (Steverink & Van Daalen, 2011).

Pierson and Sterman (2013) have developed a behavioral dynamic airline industry model to investigate the roots of the cycles since the deregulation established in 1978. The model includes the endogenous capacity expansion, demand, pricing, costs and other feedbacks in that several strategies are tested to alleviate the cycles (see Figure 3.9

and Figure 3.10). They used maximum likelihood methods to estimate both partial and full model parameters while Markov Chain Monte Carlo methods are employed to set up confidence intervals. It's found in this study that the delay in capacity acquisition does not have very influential impact on profit cycle. Aggressive revenue (yield) management policy plays the main role by increasing and decreasing the prices to ensure the high seat load factors, which results with varying variances in profit (Pierson & Sterman, 2013).

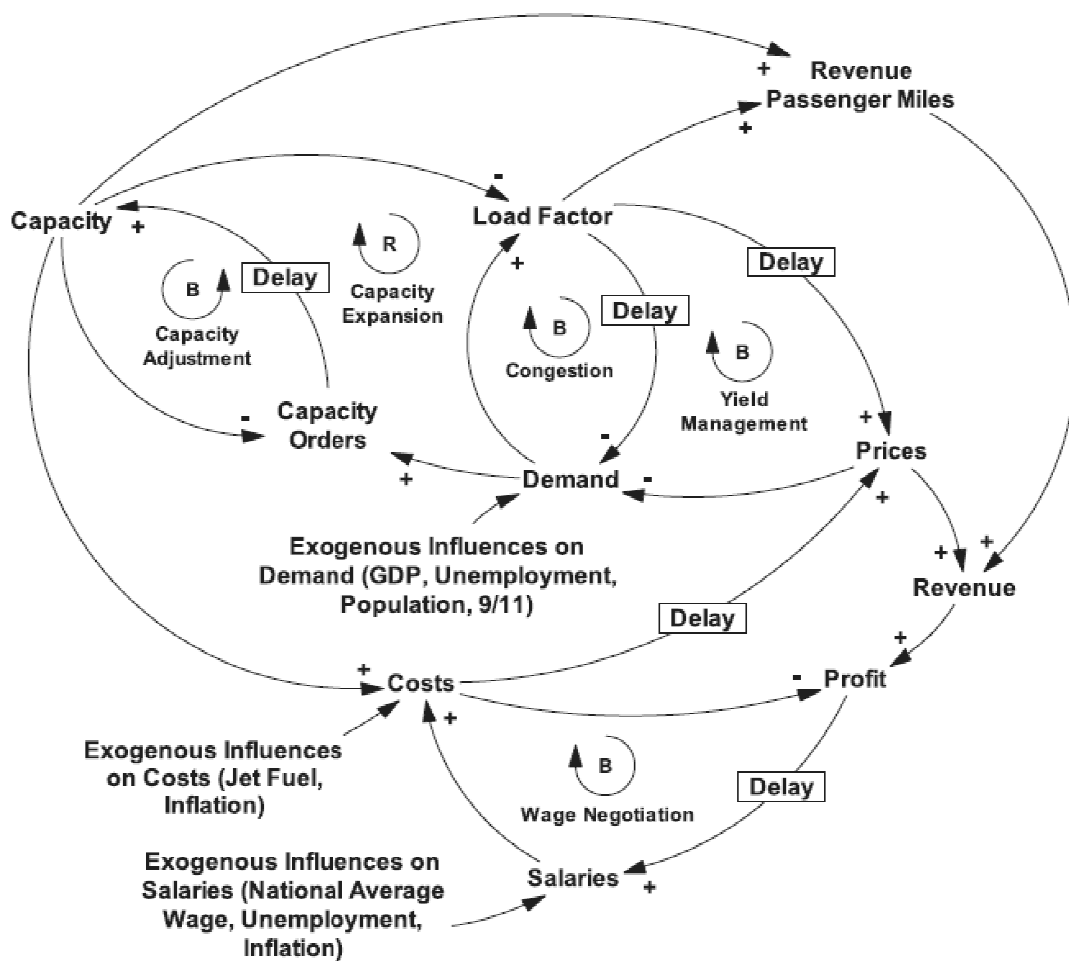


Figure 3.9. Overview of the Model Feedback Structure and Boundary (Pierson & Sterman, 2013).

As in the previous system dynamics studies, they also found evidence that cycles were caused by the late realization of the delays in negative feedbacks that try to regulate the demand, capacity, load factor (capacity utilization), and prices. However, contrary to the

previous studies, they found that the cycle in the capacity can be smoothed by adopting airline pricing policy, especially usage of the revenue management increases the responsiveness of prices to changes in demand compared to the capacity and raise the average load factors. Thus, airline pricing business rules increase both operational leverage and the variability in the profitability and can provide a globally minimum risk-return space for the industry. In summary, profit cycles are usually induced by the late recognition of the delays in the negative feedbacks (Pierson & Sterman, 2013).

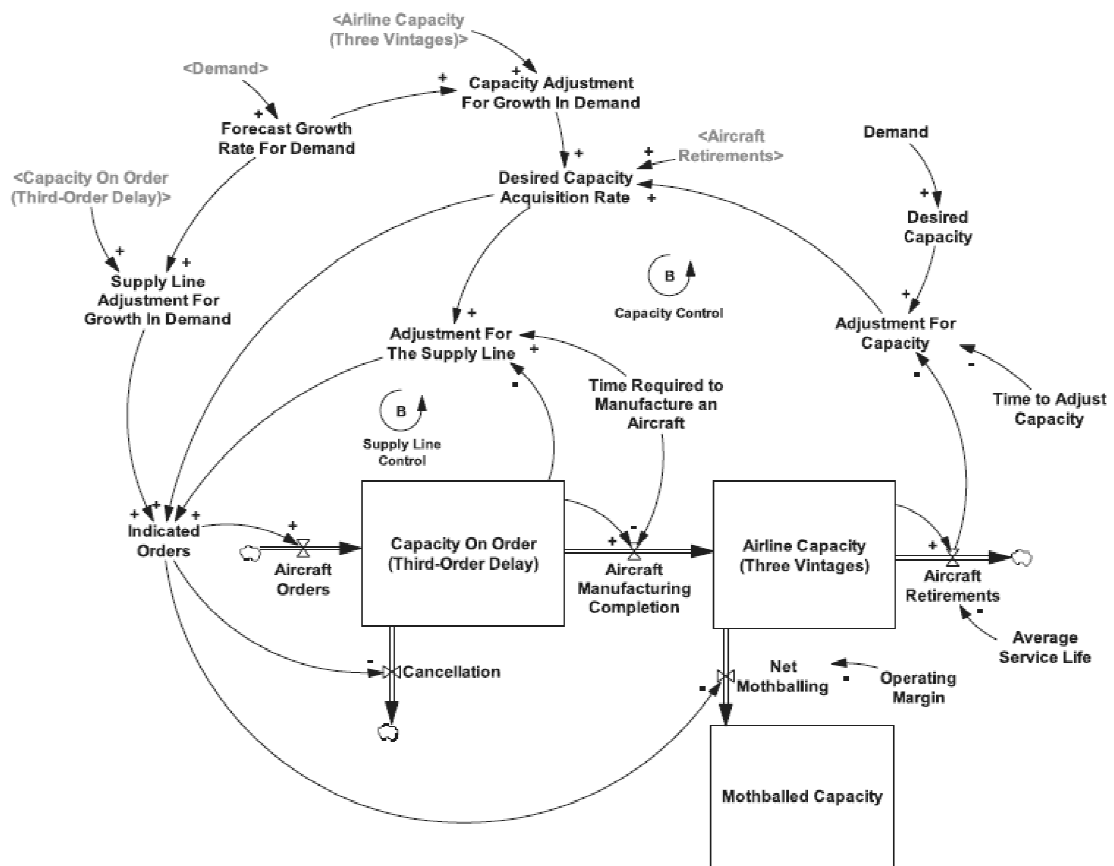


Figure 3.10. Overview of Capacity and Capacity Acquisition (Pierson & Sterman, 2013).

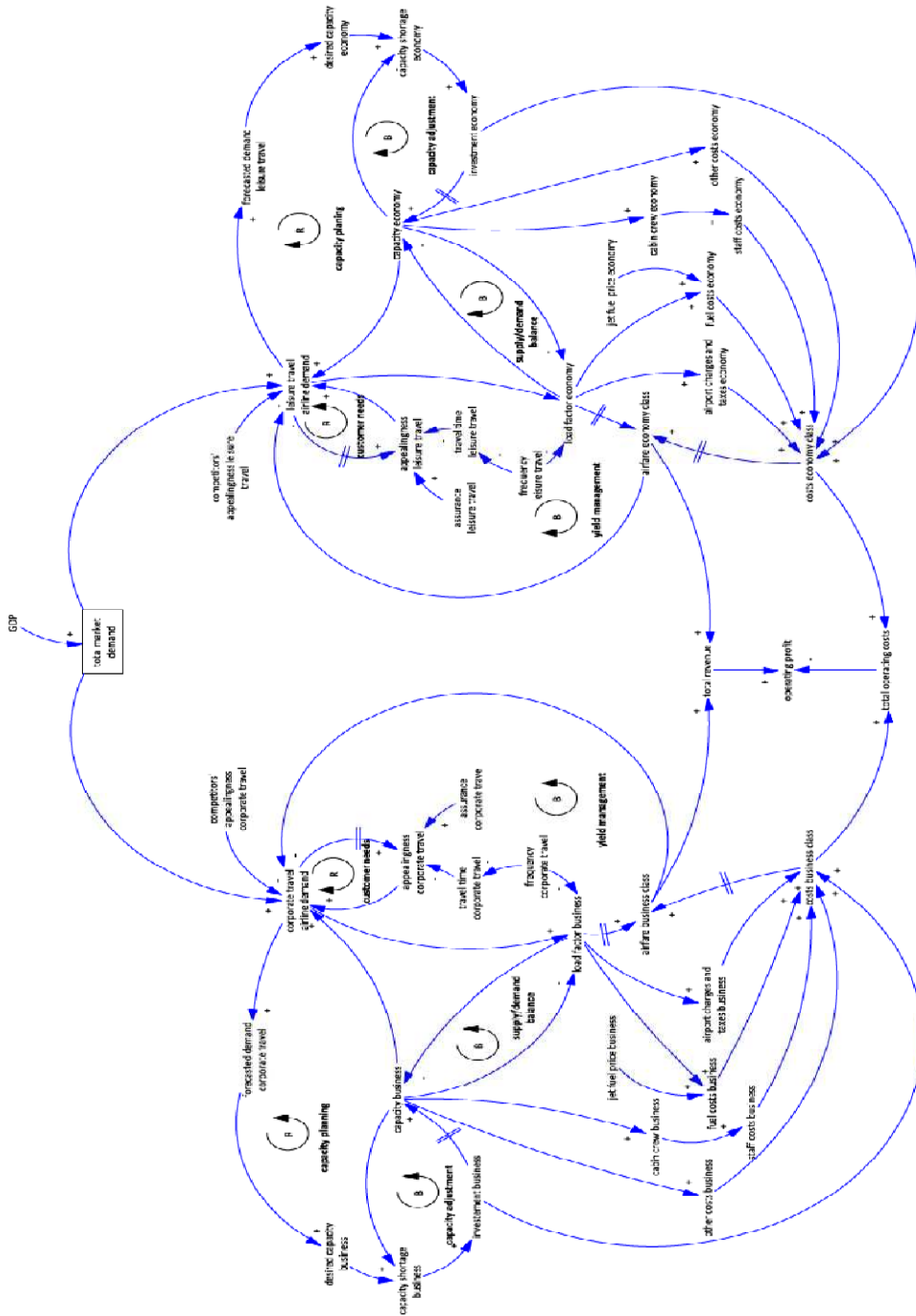


Figure 3.11. Initial Airline Causal Loop Diagram (Von Beuningen, 2014)

The study of Von Beuningen (2014) aims to identify the competitive resources of four airlines by adopting system dynamics in combination with resource-based view. The four airlines group are Cathay Pacific, Emirates, Lufthansa, and Singapore Airlines whose competition is investigated on the routes between four German Airports and three top financial centers in Asia, namely Hong Kong, Singapore and Tokyo. The open source data of airlines and limited surveys are used to study the resource of the companies. Three competitive resources, namely airfare, travel time and appealingness are designed to control the model. Likewise, it was possible to observe the cause and effect results inside the individual airline system and among the all airline players by changing one or more of these variables. The casual loop diagram model is split into three sub-tasks, namely demand, capacity and costs. These sub-models are merged based on leisure and corporate (business) travel and then interrelated at high level as seen in Figure 3.11. One reinforcing loop, namely customer needs, and three balancing loops, namely demand/supply balance, yield management and capacity adjustment, are highlighted. Several hypothesis are suggested and tested in the study (Von Beuningen, 2014)

4. SD BASED MODEL DEVELOPMENT FOR AIRLINE MAINTENANCE OPERATIONS

Turkish Airlines has significantly increased airline passenger transportation capacity in last decade from 10.4 to 50 million passengers between years 2003 and 2013 respectively (THY, 2015a). Turkish Airlines is the most dominant local airline company in the aviation industry in Turkey. Especially, domestic airline transportation demand is almost met by Turkish Airlines. It expanded both domestic and international destinations especially in the last decade and reached up to 241 (199 international and 42 domestic) different flight destinations worldwide by the end of 2013 (THY, 2015b). Compared with the other local airlines, it has the highest amount of market share and the market share of other local small airlines can be ignored for now.

Turkish Airlines currently has approximately 260 aircrafts and ordered nearly 200 brand new aircrafts to incorporate its fleet to become a worldwide airline carrier brand. The expansion of the airline fleet will have impacts in all airline operations. At the beginning of study, we aimed to investigate the relations and resulting impacts in the whole company departments. But, due to the limited open source and proprietary data issues we could not obtain enough data to model the whole company and constrained our focus on the MRO department.

When airline operations examined in the literature, unfortunately, there is almost no contemporary study that focus on the relations between MRO activities and other airline operations. So, this study aimed to fill this gap in literature by using very limited available data about Turkish Technic MRO department. The publicized data is very limited and like other airlines, Turkish Airlines also prefers to keep its data as private. Therefore, it is decided to start the study as a case study.

In summary, this section explains the adoption of system dynamics methodology to the Turkish Technic MRO department.

4.1. Problem Definition

There are lots of airline operations including, but not limited to, flight scheduling, fleet assignment, aircraft routing, crew scheduling, manpower planning, revenue

management, fuel management systems, airline irregular operations, gate assignment, aircraft boarding strategy, airline operations and scheduling (Bazargan, 2010). In these operations, direct MRO activity cost is very significant and it is approximately around 10% of the all other cost drivers as shown at Table 1.1. (Merkert, 2010)(Von Beuningen, 2014). When MRO activities are handled in an unsatisfactory manner, this situation causes more aircrafts to lose their airworthiness. The aircrafts sitting on the ground means losing revenues, and burdening additional costs.

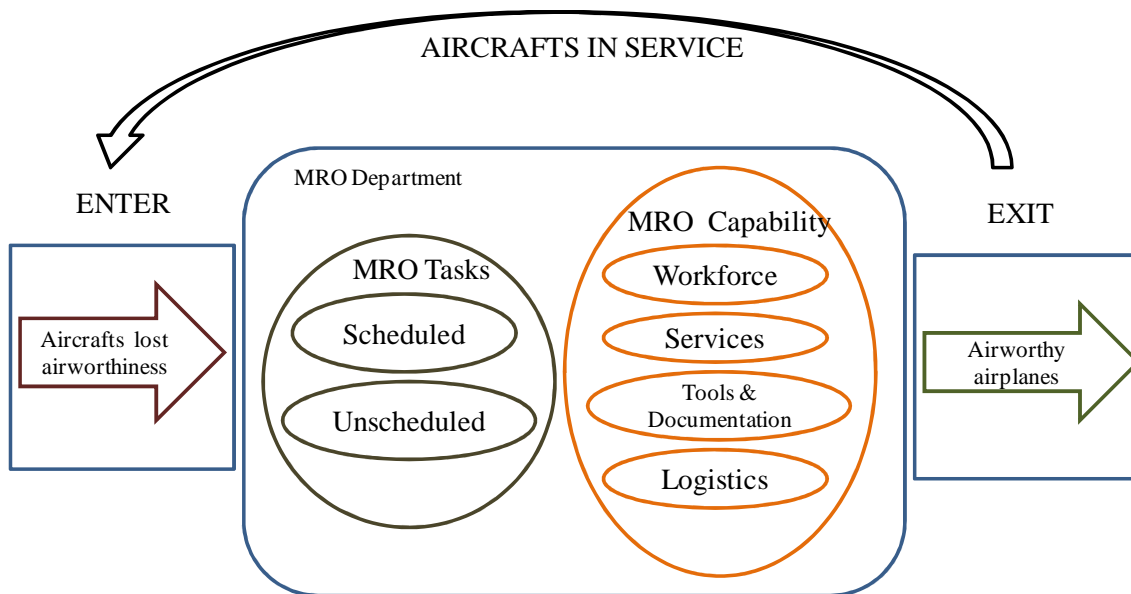


Figure 4.1. Maintenance Cycle in a MRO Facility

There are some studies that aim to model the operations and activities in airline industry as mentioned in literature review section. The cause-effect relationships of the MRO activities with the other airline operations are not investigated in detail at these studies. That is why; this study will try to shed some light to model and reveal the interactions of the MRO activities within the airline operations by using system dynamics modeling methodology.

Aircrafts usually need a wide variety of periodic maintenance activities in order to sustain their airworthiness. These activities are generally called as A, B, C and D checks. The tasks in these certain checks can be transferred or handled in other type of checks. For instance, B checks can be executed in A and C checks as in Turkish Technic. C checks can be divided into C1 and C2 checks (Hasekioglu, 2014). The

contents, means and volume of maintenance activities covered in these checks differ according to aircraft type. They are well planned routine tasks which are triggered after reaching a certain operation condition such as flying time, age, number of flights and executed periodically as seen in Figure 4.1. Other than this planned MRO tasks, there are also unscheduled breakdowns, or detected malfunctions during inspections. The size of this unscheduled MRO tasks are not small and can reach to almost 60% of regular scheduled tasks (Hasekioglu, 2014). The strategy to execute these MRO tasks may differ from maintenance department to maintenance department and for Turkish Airlines fleet a summary is given at Table 4.1.

The MRO activities of Turkish Airlines fleet are handled by the both Turkish Technic and Turkish HABOM¹ Maintenance Departments which are the subsidiaries of Turkish Airlines Companies. Turkish Airlines ordered approximately 200 aircrafts lately and try to increase its share in the airline market². This study will investigate how the aircraft fleet growth will affect the productivity of the Turkish Airline MRO Departments and will propose some scenarios to incorporate new MRO Operations Staff to cope with this new situation.

Table 4.1. Turkish Airlines Major MRO Check Types

MRO Type	SUMMARY
A Check	It needs to be applied every week. The required MRO man power is approximately between 100-500 man-hour for each aircraft
C Check	It needs to be applied at every 2-3 years and almost takes 1 month period to finish. The required MRO man power is approximately 5000 man-hour for each aircraft.
Line Maintenance	This work is handled by approximately 500 MRO operations staff.

The scheduled and unscheduled MRO activities for any kind of aircraft requires fulfillment of a wide variety of tasks. The difficulty and time required to finish those task are not the same. So, while modeling the A and C type MRO activities, these issues are raised as challenging ones. Later, in order to keep the model simple and understandable, it is decided to convert these tasks to resource need, in another word, to

¹ Recently HABOM joined to Turkish Technic.

² The total number of aircraft in the aircraft fleet is around 264 currently (THY, 2015c).

the man power (man-hour). From judgment and past experience, the required resource for A type MRO checks, which are executed approximately on weekly base, is estimated between 100-500 man hour for each aircraft. On the other hand, the tasks executed for A type check may also appear unexpectedly by pilot observation or during routine flight checks. The C type MRO checks, which are executed on 2-3 years base, is estimated as in the order of 5000 man hour for each aircraft. In the model, the man power needed for unscheduled A and C type MROs are estimated as the 60% man power of each scheduled MRO check group based on expert experience and judgment (Hasekioglu, 2014).

Each MRO operations staff has 8 hours potential working hours daily. But, he/she has legal rights like tea breaks and almost 1.5 hours/day is spent likewise. Therefore, on average, only 4.5 working hours can be used effectively to produce value for the department. So, the utilization of one staff is around $4.5/(8-1.5)= 0.6923$. MRO operations staff also leaves from department due to the retirement or any reason and it is around 5% of the total MRO operations staff yearly. The MRO departments do not have a regular staff recruitment policy. The existing historical staff population including the administrative staff can be seen at Table 4.2.

Table 4.2. Existing MRO Staff Data

Year	Approx. Total # of MRO Staff	Total # of Aircrafts
2003	2000	65
2004	2250	73
2005	2500	83
2006	3000	103
2007	3000	102
2008	3500	127
2009	3500	134
2010	3500	152
2011	4000	179
2012	4500	202
2013	5000	244

Not all of the MRO operations staff execute the A and C type operations. Almost 500 of them are used in line maintenance operations. Therefore monthly potential man power is calculated by excluding this resource. The average number of MRO staff per aircraft

according to years can be seen at Figure 4.2. There is a decline in the ratio possibly as a result of increasing the productivity of MRO department.

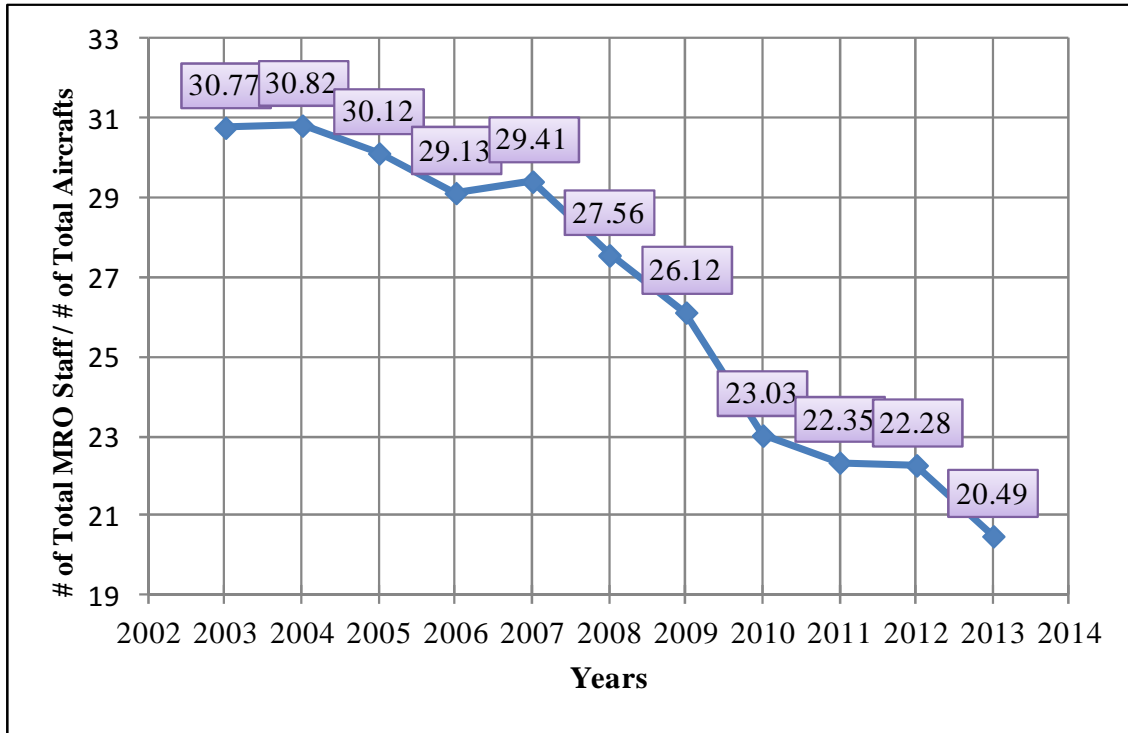


Figure 4.2. Number of Total MRO to Number of Total Aircrafts Ratio

This potential man power is used in both A and C type scheduled and unscheduled MRO operations. As an approach in the model, it is assumed that C type MRO checks last nearly one month and resource allocation priority is given to finish these tasks. After that, remaining resource is used to handle the A type checks (scheduled and unscheduled). As the time step is selected as monthly, the unfinished aircrafts at C type MRO checks will stay at least one more month in the MRO department. That is why, priority is given to the C type checks. After finishing all the MRO operations, the model store the remaining man power to observe if company has excess or spare human resource. The purpose of storing this spare resource is to see the flexibility at hand.

Another important factor directly affecting the model is the number and the timing of aircrafts that is going to join the aircraft fleet. New aircrafts will have impact on the increase of number of passengers and extra burden on the MRO facility. Thus, different

combination of sizing and timing of new aircrafts and its effects on MRO operations will be investigated.

4.2. Causal Loop Diagram of the Model

Most of the SD models use parameters at macro level instead of micro level and adopt policies, behavioral trends and changes in highly aggregate way. Therefore, these kinds of models are abstract, simple and general in that they mimic the real world system under question. While deciding to use such abstract models, the level of detail and their dynamics are sometimes sacrificed. In these cases, components of the models can be disaggregated and refined to get more sound numerical output (Abbas & Bell, 1994). Considering these facts, to make the model understandable, the detail in the model kept in the macro level in an aggregated manner.

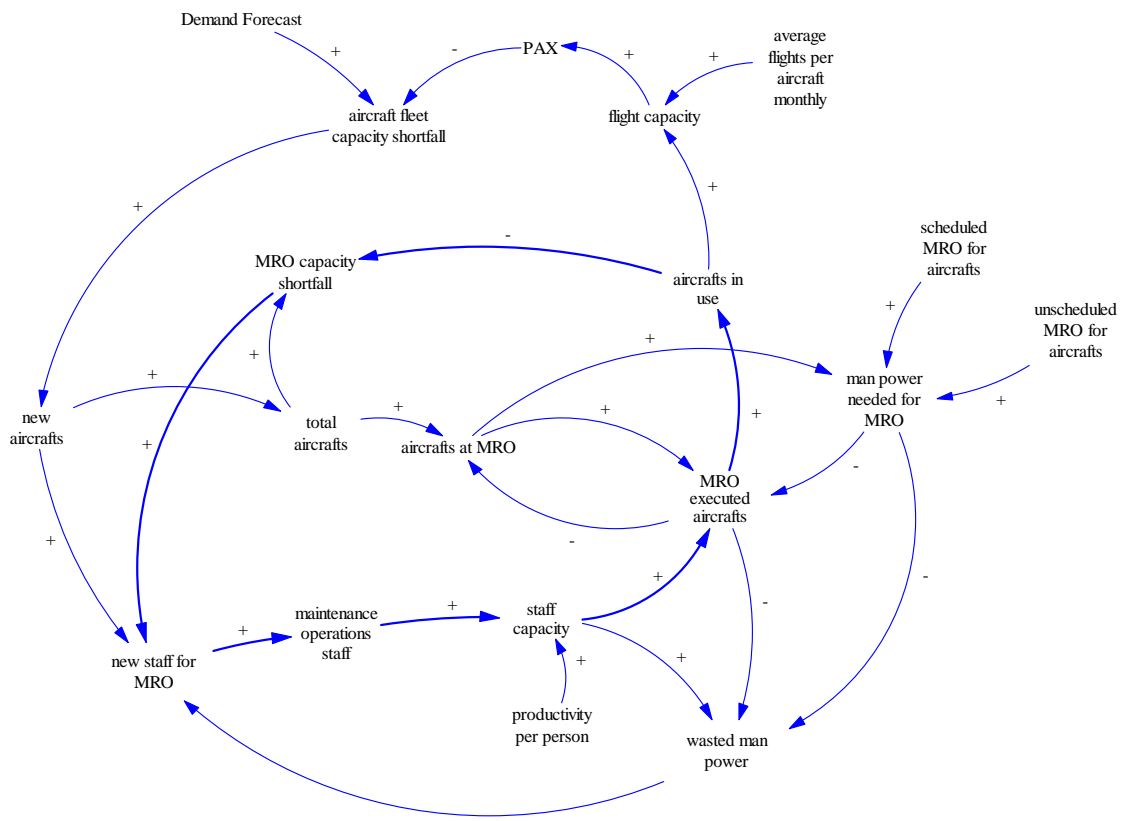


Figure 4.3. Overview of the Model Structure and Boundary

Figure 4.3 shows a high-level causal diagram summarizing the principal feedbacks and their influences in the model. A summary of the model boundary, listing the main endogenous, exogenous and excluded variables are provided at Table 4.3.

Table 4.3. Model Boundary Diagram Emphasizing the Most Important Endogenous, Exogenous and Excluded Variables in the Model.

Endogenous Variable	Exogenous Variable	Excluded Variable
Maintenance Operations Staff	Staff Look-Up Table	GDP
Staff Increase	Hour available per person	Marketing
Monthly staff capacity	Utilization Rate	Advertising
Productivity per person	Aircraft look-up data	Jet Fuel
Used man power	Passenger Demand Forecast	Inflation
Man power wasted	Scheduled A type MRO man power per aircraft	Unemployment
C Type MRO executed aircrafts	A type MRO Generator	Runway capacity
A Type MRO executed aircrafts	Weekly A Type MRO checks in a month	Aircraft Delivery
Man power need for A type MRO per aircraft	Scheduled C type MRO man power per aircraft	Wages
Man power need for C type MRO per aircraft		Brand image
Unscheduled A type MRO man power per aircraft		Budget
Unscheduled C type MRO man power per aircraft		
Actual aircrafts in use		
Average flights per aircraft in a month		
Flight capacity per month		
Purchase of aircrafts		
Potential Aircrafts to Use		
Aircrafts at C Type MRO		
Aircraft Retirement		
Total aircrafts		
Passengers per month		
Passengers		
Average number of passengers in a flight		
Man power per aircraft		
MRO capacity shortfall		
Aircraft capacity shortfall		

The model is organized into four principal sectors: resource requirement calculation for MRO checks, MRO human resource management policy, aircraft MRO planning policy and passenger capacity.

The main limiting resource that affects the MRO activity is the availability of the skilled man power. There are also other kinds of issues affecting the MRO such as ground services equipment, hangars, and maintenance tools. The effects of such things are incorporated in model with the “productivity” variable of staff.

Boundary diagrams are very useful to capture the overall structure, constraints and limits of system under investigation.

The main feedback loops at the casual loop diagram are summarized at the following paragraphs.

MRO capacity shortfall loop (see Figure 4.4) states that when MRO activity tasks requiring more man power are introduced into the system, the aircrafts usually may be accumulated at MRO facility and as a result, company may lose significant revenue. Thus, MRO operations capacity has to be increased in this case either by hiring new staff or improving the productivity of the staff. In this case, an additional MRO capability increase will be observed and this increase will help to handle more aircraft maintenance.

The balancing loop is triggered after observing a significant passenger seat capacity loss due to the unsatisfactory MRO capacity to handle MRO needs. Even though fleet size is large enough to carry the intended passenger demand, the aircrafts may not meet this call as some of them lose their airworthiness and waiting to be repaired or checked.

A significant gap between total aircrafts and actual aircrafts that in use triggers recruiting new MRO staff. This new staff will increase the number of total MRO operations staff and subsequently MRO staff capacity. This new capacity will help to handle the MRO activities of more aircrafts and increase the size of the aircraft fleet that is actually used to carry goods. Increase of the airworthy aircrafts will reduce the gap between total aircrafts and actual aircrafts in service (aircrafts in use).

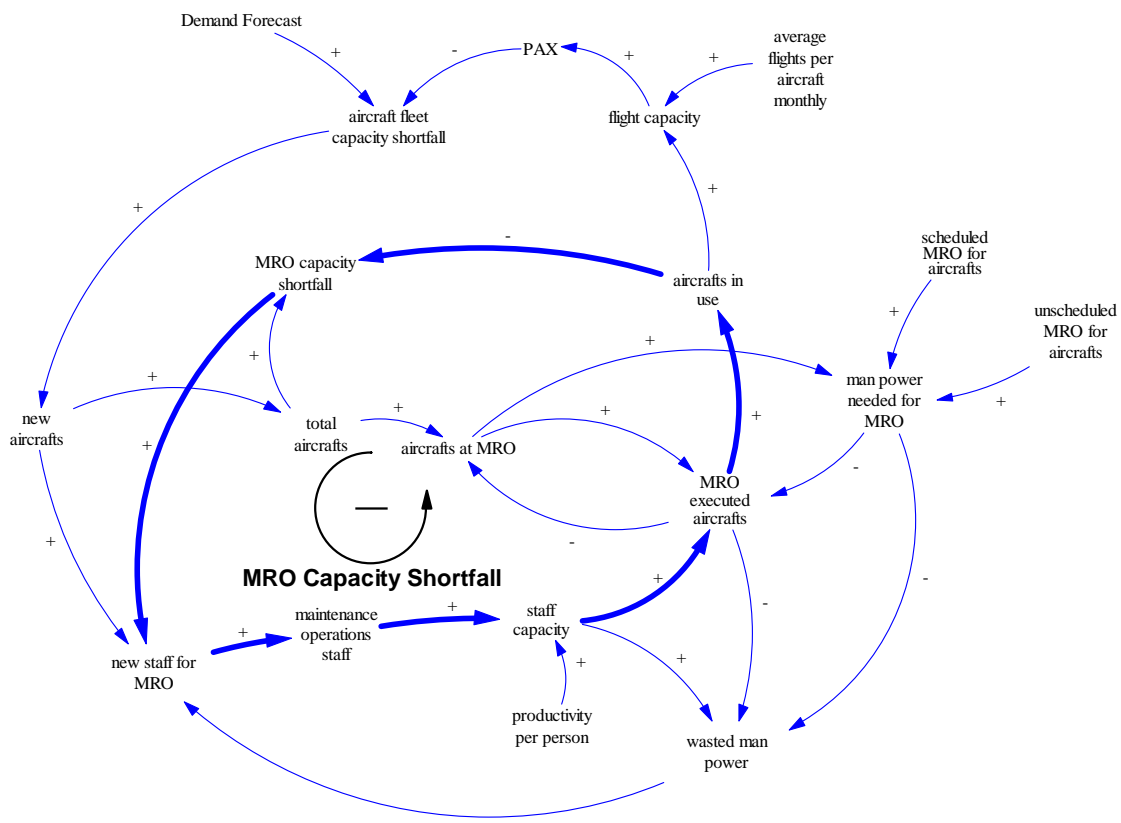


Figure 4.4. MRO Capacity Shortfall Feedback Loop

Flight capacity expansion loop (see Figure 4.5) simply states that procuring new aircrafts will usually increase flight capacity and as a result aircraft fleet will carry more passengers. The trigger to increase the flight capacity is usually the observation of the demand increase towards the airline and lack of the capacity to carry those passengers, that is, aircraft fleet seat capacity shortfall.

After reaching the triggering point of the balancing loop, new aircrafts will be integrated to the fleet to meet the passenger demand. New aircrafts will increase the fleet size and if MRO capacity allows, more aircrafts will undergo to MRO operations to sustain their airworthiness. This will initiate a chain relation as more aircrafts in use to more flight capacity and more flight capacity to more passengers. After all, loop will be enclosed by decreasing the gap between passenger demand forecast and available seat capacity for passengers.

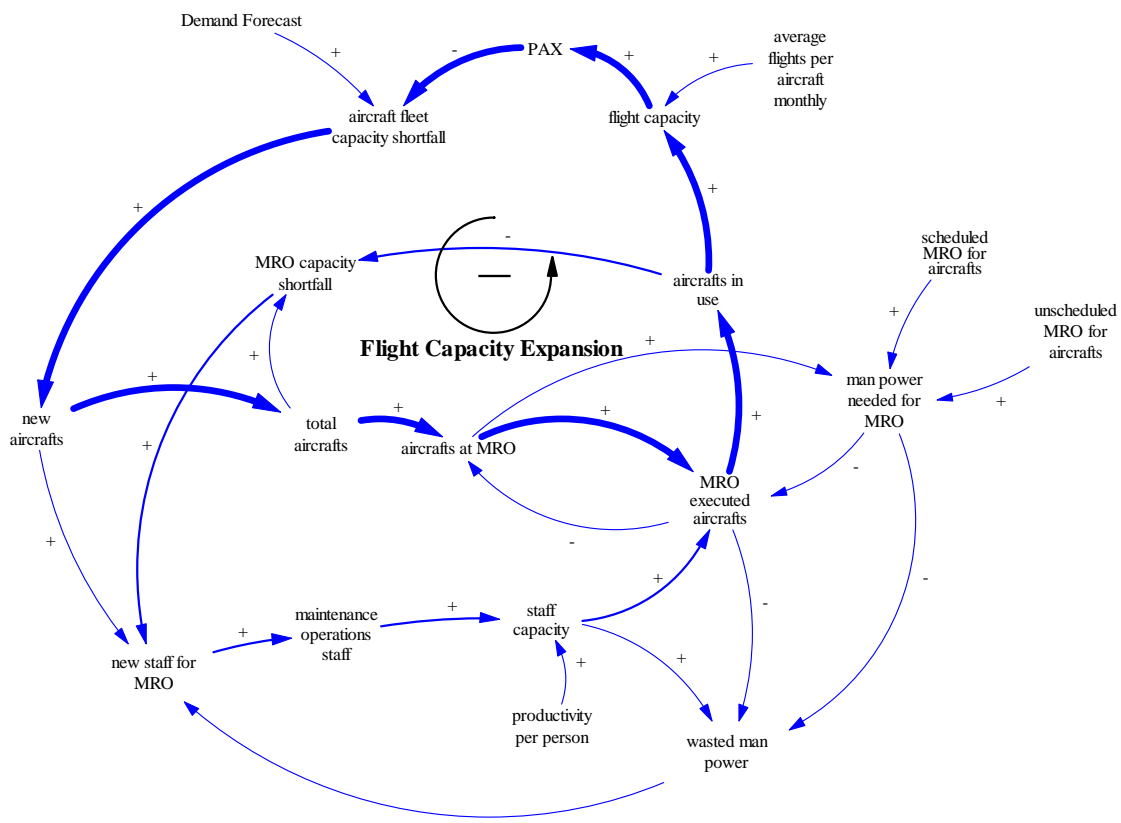


Figure 4.5. Flight Capacity Expansion Feedback Loop

The impact of fleet expansion on MRO capacity loop (see Figure 4.6) states that a net increase in the fleet size usually requires more MRO capacity to handle the new aircrafts' MRO needs. That is why, it is reasonable to consider recruiting new MRO staff while acquiring new aircrafts. Otherwise, the company may not reach the intended flight capacity and will lose revenue as some portion of the aircrafts will be waiting on the ground to become airworthy. On the other hand, hiring additional MRO staff is a cost to the company and a balance is required between revenue losses due to the shortfall of MRO staff capacity and costs of hiring additional MRO staff. The ultimate goal may be to minimize both these relevant costs and maintenance service durations simultaneously.

If the significant gap between demand forecast and passengers is not caused by the capacity shortfall of the MRO facility then a triggering action initiated from aircraft fleet capacity shortfall to minimize this gap. Basically, procurement of the new aircrafts indirectly introduces more MRO activities to the MRO facility. So, procurement of new

aircrafts causes to recruit additional MRO staff to meet the MRO needs of these new aircrafts. Thus, enhanced MRO capacity will service to more aircrafts. This will increase the number of aircrafts in service and as a result, the flight capacity. Elevated flight capacity will usually result with carrying more passenger and closing the afore mentioned gap.

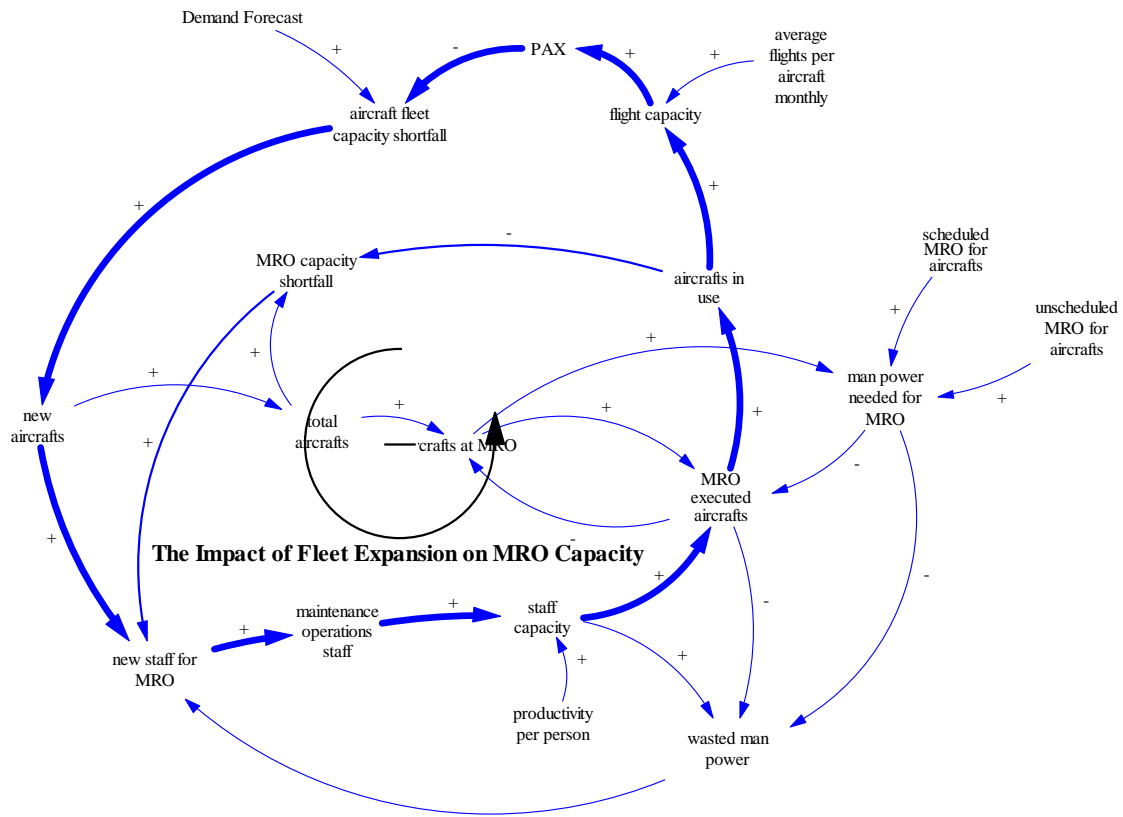


Figure 4.6. The Impact of Fleet Expansion on MRO Capacity Feedback Loop

Man power waste loop (see Figure 4.7) highlights the situation in which there are excess resources that do not produce any value to the system and wait idle. In case of procuring new resource, this excess resource capacity can be considered and a portion of it can be subtracted from the planned new resource. Likewise, the company can save from unnecessary costs. Another option may be to use this idle resource at giving MRO service to the other airlines. The loop is triggered if there exists a significant idle resource. In any case, this spare man power also can be considered as insurance during the periods of elevated MRO operations.

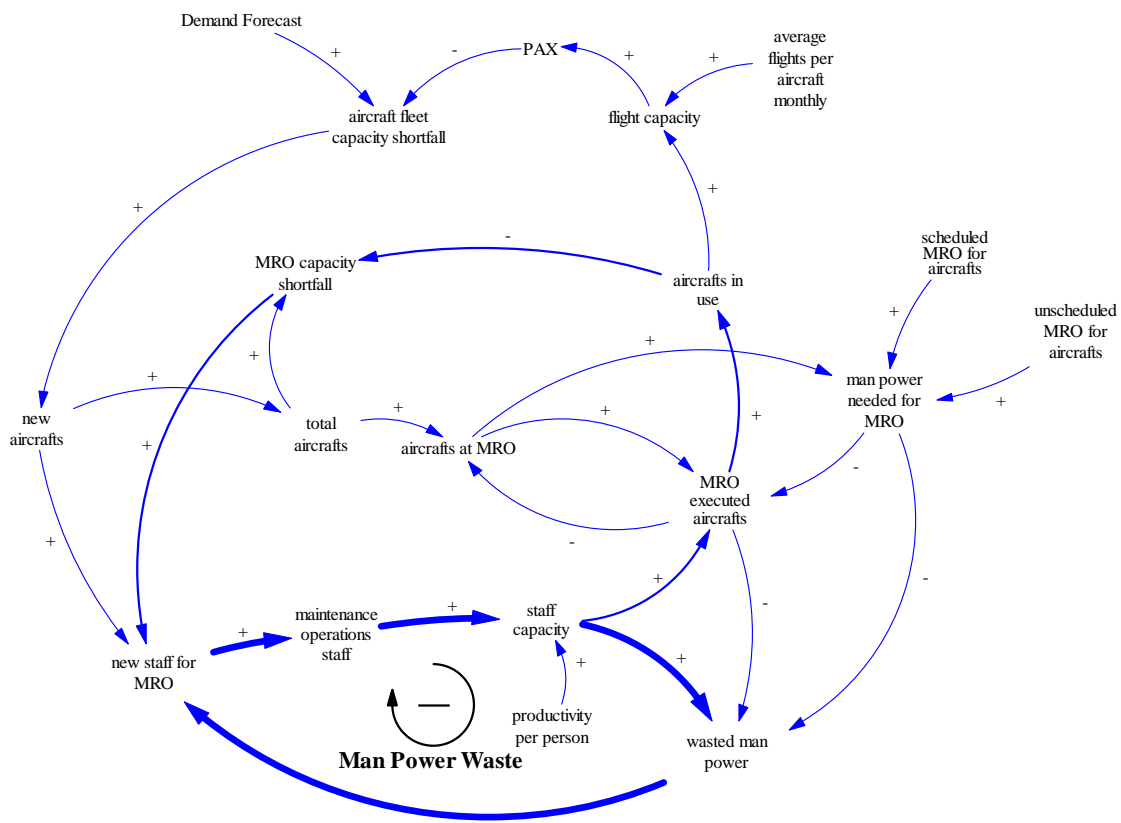


Figure 4.7. Man Power Waste Feedback Loop

Efficient usage of resource loop (see Figure 4.8) indicates that when a high portion of available resource is used to produce value, which is to handle MRO needs of the fleet, then the resource in hand will not be wasted and will result with less cost and more revenue. The MRO need of more aircrafts will be answered. If there is a balance between the volume of the MRO capacity and the MRO needs of the aircraft fleet, MRO capacity will not be wasted. But the regulation of this balance is not easy due to the stochastic nature of MRO operations.

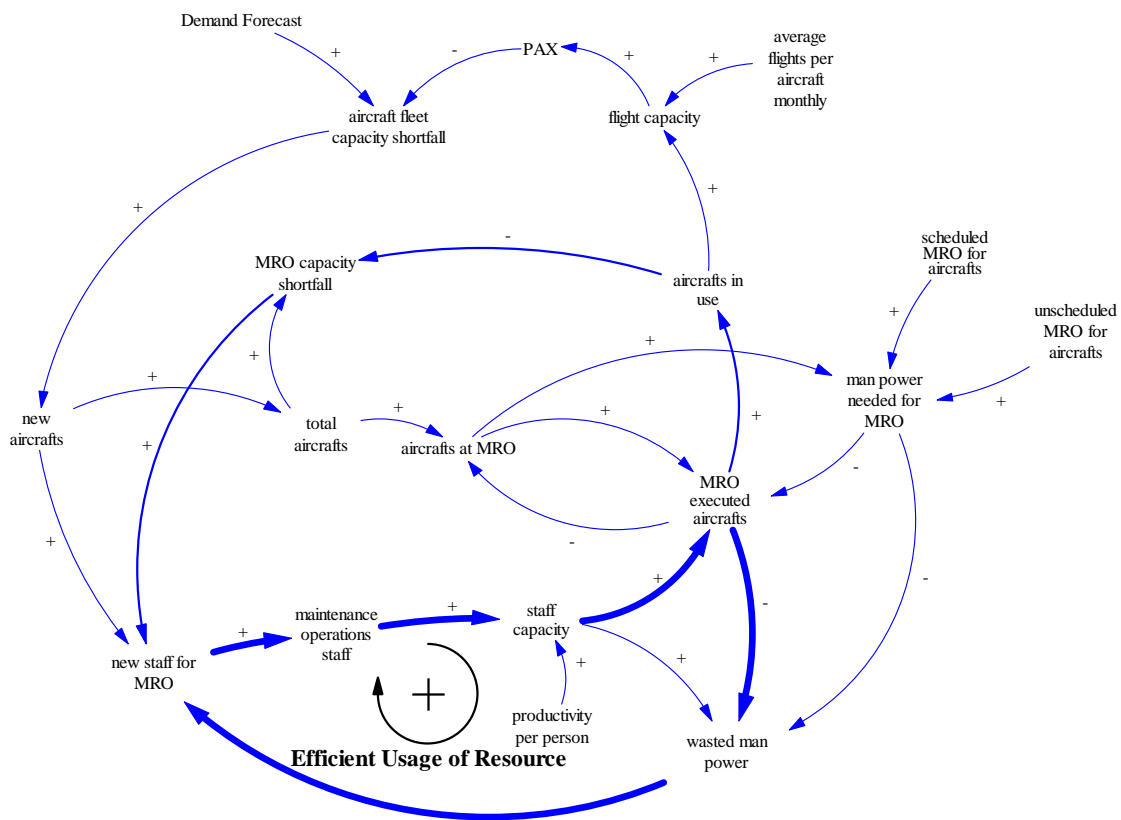


Figure 4.8. Efficient Usage of Resource Feedback Loop

Effect of increased MRO activity on MRO utilization loop (see Figure 4.9) indicates that when system introduces high volume of MRO activity, then this will affect the utilization of MRO facility. If MRO facility has idle resource, then this resource can be used to compensate the unexpected additional burden and increase the utilization of the MRO facility. In case of inadequate MRO resource, this high MRO burden will cause less aircrafts to be serviced. On the other hand, wasted man power will be reduced to minimum levels. To overcome the situation of insufficient resource, MRO staff capacity has to be increased.

Staff capacity can be increased not only by increasing the staff productivity but also by recruiting additional staff. Likewise, overall MRO activity is also increased in two ways: One is to increase the number of aircrafts that need MRO and the other is to enhance the content of the MRO which requires more man power. The increased MRO tasks will consume more resources and, as a result, the utilization of MRO operations staff will also increase. But, keep in mind that this does not guarantee the increased

productivity for MRO department. Because the concrete output of MRO department can be measured with number of airworthy aircrafts. This number may not be increased due to the likely increased volume of MRO tasks, even though the utilization of MRO operations staff is increased.

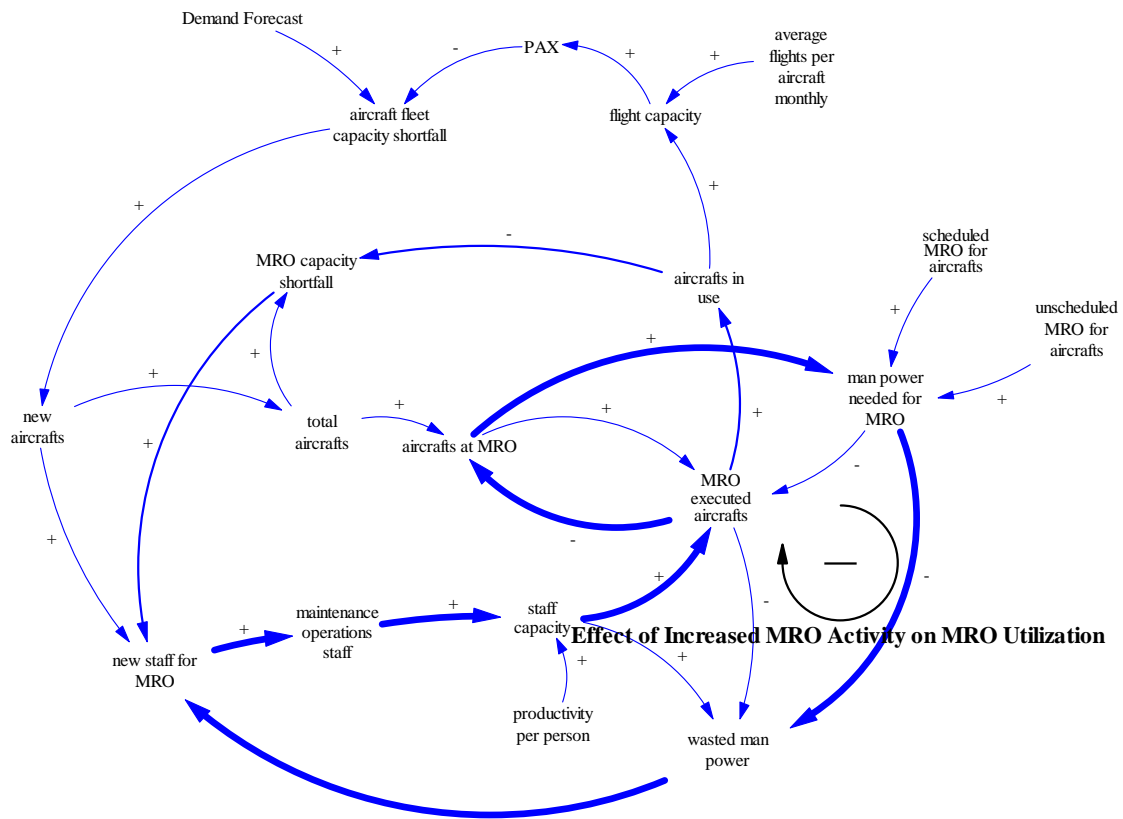


Figure 4.9. Effect of Increased MRO Activity on MRO Utilization Feedback Loop

MRO activity increase loop (see Figure 4.10) indicates that an increase in MRO activity man power due to any reason, such as the increase in the number of aircrafts that need MRO or enhancement of the content of the MRO which requires more man power, will bring forth the fact the there will a backlog at MRO facility consist of aircrafts that need MRO and size of the serviced aircrafts in the fleet will be lessened. Thus, aircrafts at MRO facility will be accumulated.

Routine MRO cycle loop (see Figure 4.11) indicates that aircrafts at MRO joins the fleet to bring value to the airline company after a certain time and other aircrafts take place of these aircrafts to undergo the MRO activity.

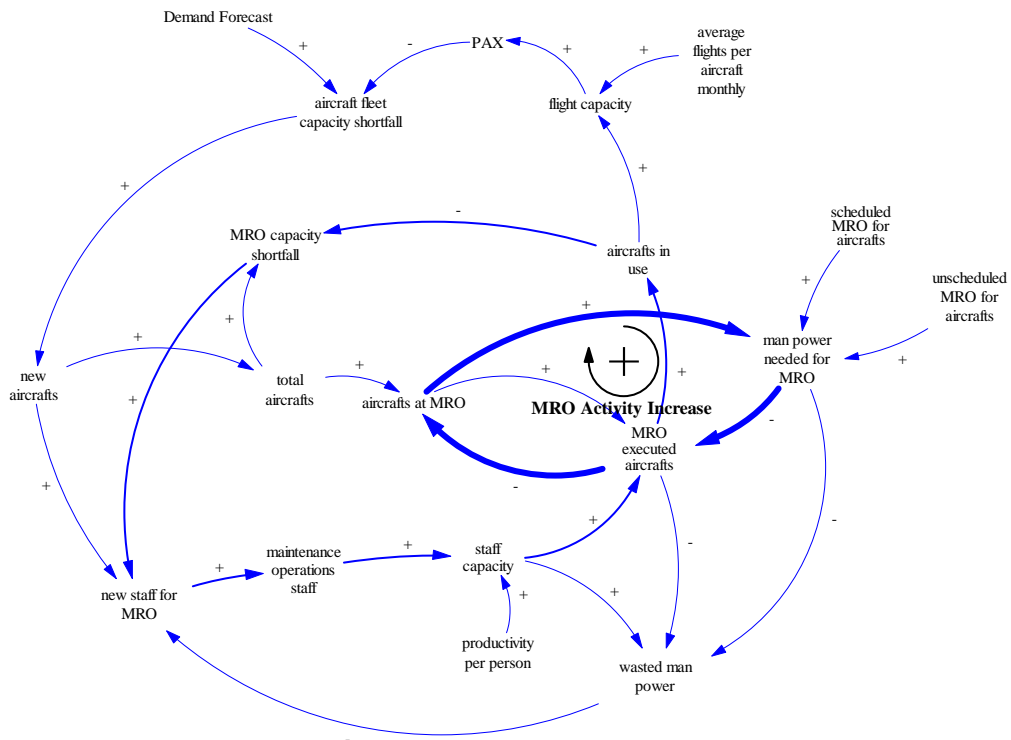


Figure 4.10. MRO Activity Increase Feedback Loop

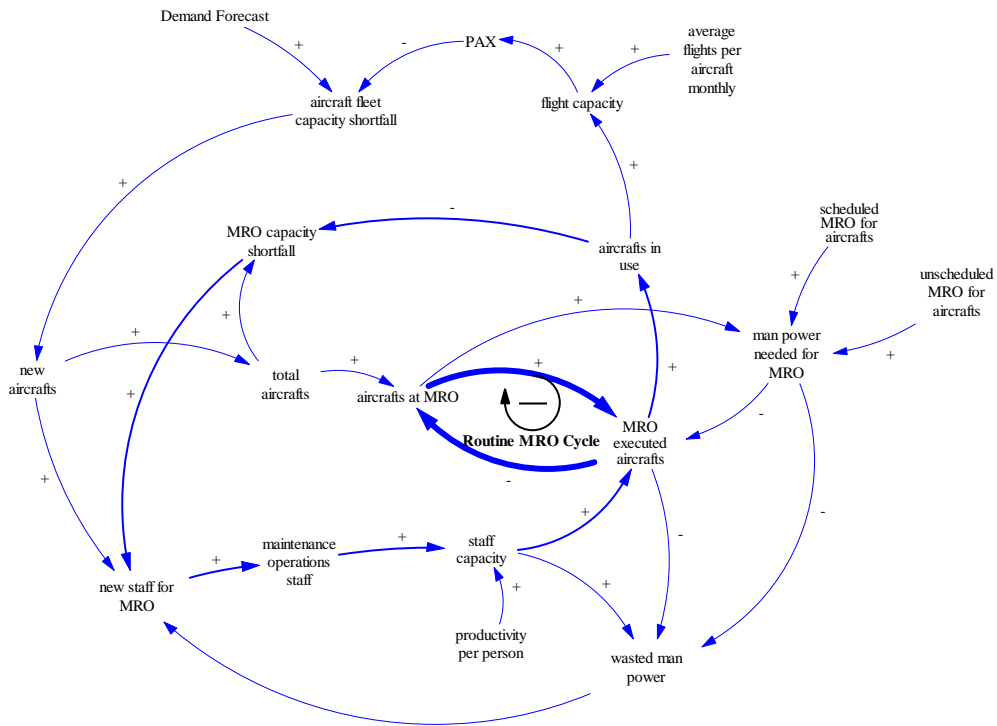


Figure 4.11. Routine MRO Cycle Feedback Loop

4.3. Stock and Flow Diagram of the Model

The stock and flow diagram of the model is presented at Figure 4.12. The model separated into sub-models to comprehend more clearly and explained in detail in the following paragraphs. The parameters used in the model are calculated from the historical data and from expert judgments and a list of them is presented in the Table 4.4.

The stock and flow diagram is implemented at Vensim DSS version 5.10d. The time horizon is start from 2003 to 2025 and time step is one month (approximately 0.08333 / Year).

Table 4.4. Parameters List

Variable	Value	Unit
aircraft retirement rate	0.00833	1/Month
C Type MRO ratio	1/2.5/12	1/Month (Total aircrafts/2.5 Years/12 Months)
C type MRO to Month ratio	1	1/Month
man per aircraft	35	man/aircraft
Potential Aircrafts to Use: Initial Value	64	aircraft
scheduled C type MRO man power per aircraft	5000	man*hour /aircraft/Month
line maint. oper. staff	500	man
Maint. Operations Staff : Initial Value	2000	man
Man Power Wasted : Initial Value	0	man
staff leaving rate per month	0.00416	1/Month
utilization per person	0.6923	
waste man power save filter	0.5	
work days in a month	24	day/Month
average number of flights per aircraft in a month	200	flight/(Month*aircraft)
average number of passengers in a flight	139	Passenger/flight
Demand Forecast : Initial Value	10400000	Passenger
Monthly aircraft shortage filtering ratio	0.5	1/Month
Passenger: Initial Value	10400000	Passenger
to month	1	1/Month
total aircraft MRO desired ratio	0.98	
Total Flights : Initial Value	100000	flight
hourly man power cost	80	Dollar/man/hour

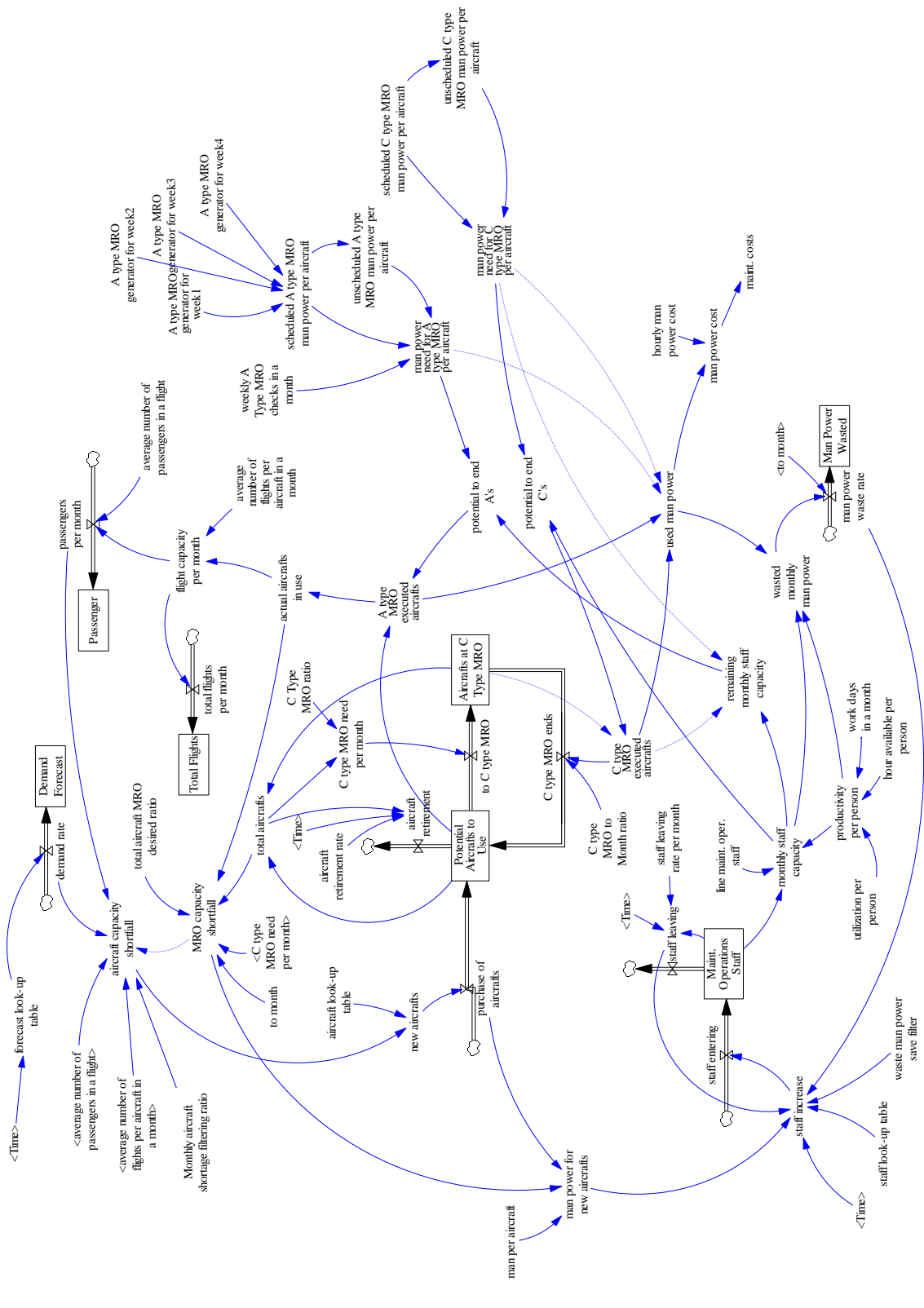


Figure 4.12. Stock and Flow Diagram of The Model

Aircraft MRO planning policy sub-model try to schedule the MRO checks of the aircrafts according to the regulations. As mentioned before, A type MRO checks are performed for each aircraft on weekly basis, while C type MRO checks are performed on 2-3 year periods and last almost one month. So, the number of aircraft that require C type MRO in a month is calculated by dividing total number of aircraft to the 2.5 years period and then to 12 months. It is assumed that aircrafts at the C type MRO check are unavailable for service during this period. That is why, all aircrafts other than the ones at C type check are potentially can be used in service provided that they are airworthy.

At the end of each month, aircrafts requiring C type check join to the “Aircrafts at C Type MRO” section and some of them leave from this section for service if they are successfully checked and repaired. There must be enough potential man power to successfully complete the MRO operations. For example, if there were 30 aircrafts at the C type MRO section and MRO facility had man power for at most 20 aircraft C type checks, then 20 aircrafts would leave from MRO facility and 10 aircraft would stay at MRO facility at least for one month period.

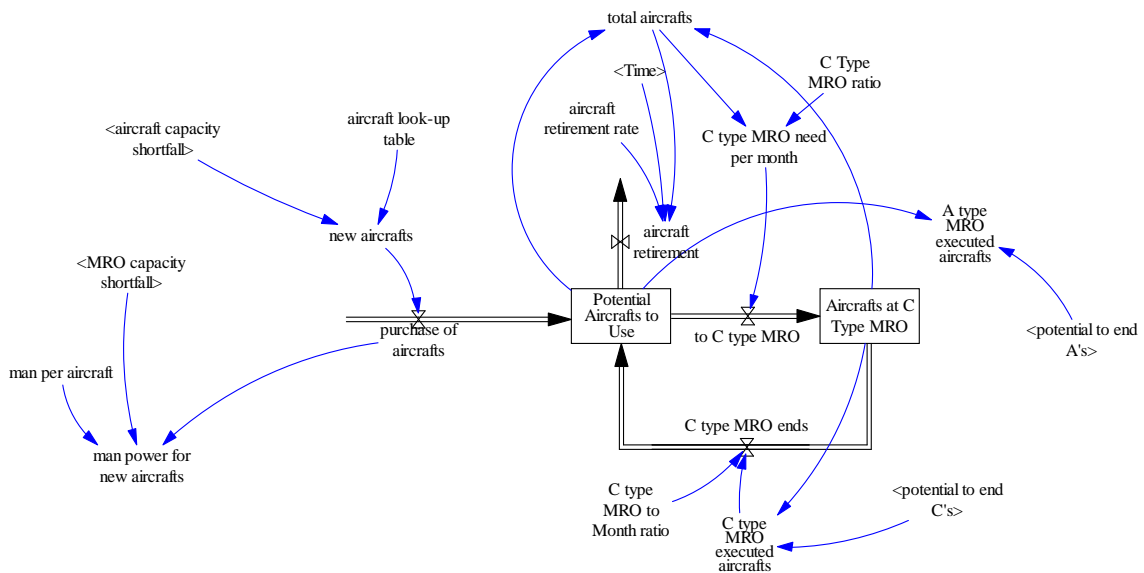


Figure 4.13. Aircraft MRO Planning Policy Sub-Model

As the size of the aircrafts increase, the volume of both C type checks and A type checks are also elevate. This will indirectly force to recruit additional MRO operations

staff. On the other hand, fleet seat capacity will be enhanced and probably will carry more passengers. More detail about Aircraft MRO planning policy sub-model can be seen at Figure 4.13 and Table 4.5. This portion of model can be detailed by adding the financial constraints to buy new aircrafts.

Table 4.5. Aircraft MRO Planning Policy Sub-Model Equations

Equation	Unit	Number
A type MRO executed aircrafts= MIN (Potential Aircrafts to Use, potential to end A's)	aircraft	(4.1)
aircraft capacity shortfall=MAX(0,INTEGER(Monthly aircraft shortage filtering ratio* (demand rate-passengers per month)/(average number of passengers in a flight*average number of flights per aircraft in a month) - MRO capacity shortfall))	aircraft/Month	(4.2)
aircraft look-up table = GET XLS DATA('MRO_Data_model.xls', 'Yearly', 'a', 'g2')	aircraft/Month	(4.3)
aircraft retirement= IF THEN ELSE(Time < 2014 ,0,INTEGER (total aircrafts * aircraft retirement rate))	aircraft/Month	(4.4)
Aircrafts at C Type MRO= INTEG (to C type MRO-C type MRO ends, 1)	aircraft	(4.5)
C type MRO ends=C type MRO executed aircrafts*C type MRO to Month ratio	aircraft/Month	(4.6)
C type MRO executed aircrafts= MIN(Aircrafts at C Type MRO, potential to end C's)	aircraft	(4.7)
C type MRO need per month= INTEGER (total aircrafts * C Type MRO ratio)	aircraft/Month	(4.8)
man power for new aircrafts=man per aircraft*(purchase of aircrafts + MRO capacity shortfall)	man/Month	(4.9)
MRO capacity shortfall= MAX(0, IF THEN ELSE((C type MRO need per month + actual aircrafts in use* to month) > total aircraft MRO desired ratio*total aircrafts*to month , 0 , INTEGER(to month*(total aircrafts-actual aircrafts in use)) - C type MRO need per month))	aircraft/Month	(4.10)
new aircrafts= MAX(aircraft look-up table, aircraft capacity shortfall)	aircraft/Month	(4.11)
Potential Aircrafts to Use= INTEG (C type MRO ends+purchase of aircrafts-aircraft retirement-to C type MRO, 64)	aircraft	(4.12)
potential to end A's= INTEGER(remaining monthly staff capacity / man power need for A type MRO per aircraft)	aircraft	(4.13)
potential to end C's= INTEGER(monthly staff capacity / man power need for C type MRO per aircraft)	aircraft	(4.14)
purchase of aircrafts= new aircrafts	aircraft/Month	(4.15)
to C type MRO= C type MRO need per month	aircraft/Month	(4.16)
total aircrafts= Aircrafts at C Type MRO + Potential Aircrafts to Use	aircraft	(4.17)

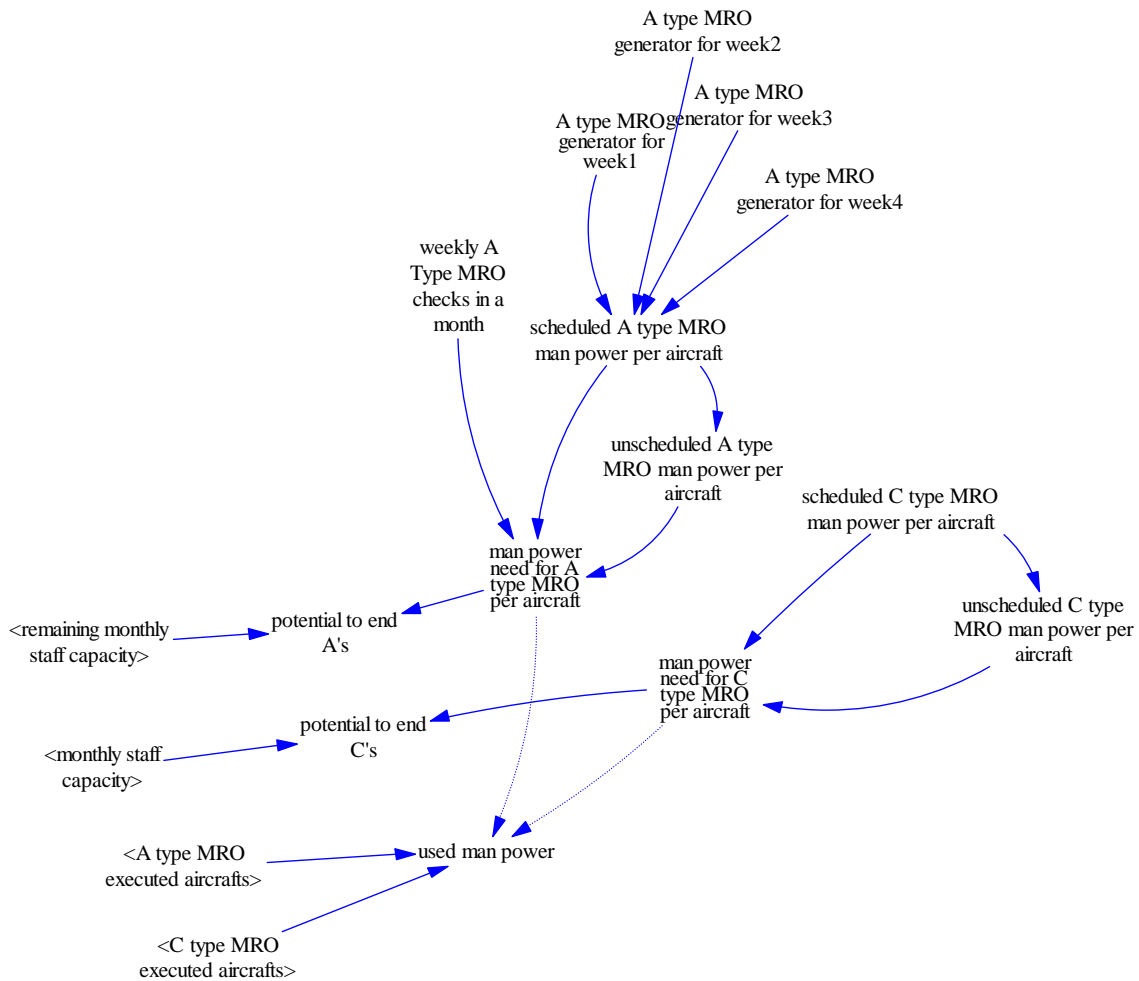


Figure 4.14. MRO Checks Sub-Model

MRO checks sub-model highlights the routine MRO checks and required man power to execute these operations. In this sub-model, two main MRO checks are considered as important and implemented. These checks are composed of thousands of different tasks and the volume and the required time to finish them are quite different. At first, it was a challenging task how to implement these tasks in the model. After discussing the issues with subject matter experts, it was decided to convert all these well defined tasks to man power, which is sometimes referred as man x hour. Every task can be converted to its equivalent man power value.

From experience, scheduled A type checks require 100-500 man x hour resource for each week while scheduled C type checks do 5000 man x hour resource at 2-3 years intervals. As stated earlier, there also unscheduled A and C type checks. From expert judgment, size of these tasks are almost 60% of the scheduled A and C type checks.

Table 4.6. MRO Checks Sub-Model Equations

Equation	Unit	Number
A type MRO executed aircrafts= MIN (Potential Aircrafts to Use, potential to end A's)	aircraft	(4.18)
A type MRO generator for week1= RANDOM UNIFORM(100,500 , 2148)	man*hour/aircraft/ Week	(4.19)
A type MRO generator for week2= RANDOM UNIFORM(100,500 , 7876)	man*hour/aircraft/ Week	(4.20)
A type MRO generator for week3= RANDOM UNIFORM(100,500 , 1974)	man*hour/aircraft/ Week	(4.21)
A type MRO generator for week4= RANDOM UNIFORM(100,500 , 1997)	man*hour/aircraft/ Week	(4.22)
C type MRO executed aircrafts= MIN(Aircrafts at C Type MRO, potential to end C's)	aircraft	(4.23)
man power need for A type MRO per aircraft= weekly A Type MRO checks in a month * (scheduled A type MRO man power per aircraft +unscheduled A type MRO man power per aircraft)	man* hour/aircraft /Month	(4.24)
man power need for C type MRO per aircraft=scheduled C type MRO man power per aircraft+unscheduled C type MRO man power per aircraft	man*hour/ (Month*aircraft)	(4.25)
monthly staff capacity=MAX (0,(Maint. Operations Staff-line maint. oper. staff)*productivity per person)	man*hour/Month	(4.26)
potential to end A's= INTEGER(remaining monthly staff capacity / man power need for A type MRO per aircraft)	aircraft	(4.27)
potential to end C's= INTEGER(monthly staff capacity / man power need for C type MRO per aircraft)	aircraft	(4.28)
remaining monthly staff capacity= monthly staff capacity- (C type MRO executed aircrafts*man power need for C type MRO per aircraft)	man*hour/Month	(4.29)
scheduled A type MRO man power per aircraft=A type MRO generator for week1+A type MRO generator for week2+A type MRO generator for week3+A type MRO generator for week4	man* hour/aircraft /Week	(4.30)
unscheduled A type MRO man power per aircraft= 0.6*scheduled A type MRO man power per aircraft	man* hour/aircraft /Week	(4.31)
unscheduled C type MRO man power per aircraft= 0.6*scheduled C type MRO man power per aircraft	man* hour/aircraft /Month	(4.32)
used man power= A type MRO executed aircrafts*man power need for A type MRO per aircraft+ C type MRO executed aircrafts*man power need for C type MRO per aircraft	man*hour/Month	(4.33)

The model assumed that MRO execution priority should be given to the C type checks, as they almost last one month. The monthly man power of MRO staff first used to finish C type checks and then remaining man power is used to finish the 4 weeks' A type

checks as many as possible. Available man power is divided by the required man power need for MRO checks so as to find the maximum number of aircraft whose checks can be completed, that is the variables “potential to end A’s” and “potential to end C’s” respectively. The detail of the sub-model can be seen at Figure 4.14 and Table 4.6.

Table 4.7. MRO Human Resource Management Policy Sub-Model Equations

Equation	Unit	Number
C type MRO executed aircrafts=MIN(Aircrafts at C Type MRO, potential to end C's)	aircraft	(4.34)
Maint. Operations Staff = INTEG (staff entering-staff leaving, 2000)	man	(4.35)
man power for new aircrafts=man per aircraft*MAX(purchase of aircrafts, MRO capacity shortfall)	man/Month	(4.36)
man power need for C type MRO per aircraft=scheduled C type MRO man power per aircraft + unscheduled C type MRO man power per aircraft	man*hour/ (Month*aircraft)	(4.37)
man power waste rate=wasted monthly man power*to month	man/Month	(4.38)
Man Power Wasted= INTEG (man power waste rate,0)	man	(4.39)
monthly staff capacity=MAX (0, (Maint. Operations Staff - line maint. oper. staff) *productivity per person)	man*hour/Month	(4.40)
potential to end C's= INTEGER(monthly staff capacity / man power need for C type MRO per aircraft)	aircraft	(4.41)
productivity per person= work days in a month*hour available per person*utilization per person	hour/Month	(4.42)
remaining monthly staff capacity= monthly staff capacity- (C type MRO executed aircrafts*man power need for C type MRO per aircraft)	man*hour/Month	(4.43)
staff entering=staff increase	man/Month	(4.44)
staff increase= IF THEN ELSE(Time < 2014, staff look-up table , MAX(0,man power for new aircrafts- man power waste rate*waste man power save filter+ staff leaving))	man/Month	(4.45)
staff leaving = IF THEN ELSE(Time < 2014 ,0,INTEGER (Maint. Operations Staff * staff leaving rate per month))	man/Month	(4.46)
staff look-up table = GET XLS DATA('MRO_Data_model.xls', 'Yearly', 'a', 'j2')	man/Month	(4.47)
used man power= A type MRO executed aircrafts*man power need for A type MRO per aircraft+ C type MRO executed aircrafts*man power need for C type MRO per aircraft	man*hour/Month	(4.48)
wasted monthly man power = (monthly staff capacity-used man power)/productivity per person	man	(4.49)

MRO human resource management policy sub-model manages the human resource need of the MRO department. While maintaining human resource policy, model takes into account of joining new aircrafts to the fleet, retiring aircrafts, wasted man power and the productivity of the employees. The business process flow and the equations used are presented at Figure 4.15 and Table 4.7. respectively. The wasted man power is taken into consideration while recruiting MRO staff. It's value is filtered with multiplication by “waste man power save filter” to sustain a more robust staff increase policy and balance the excess staff and new staff.

This portion of model can be detailed by adding the financial constraints to recruit MRO operations staff.

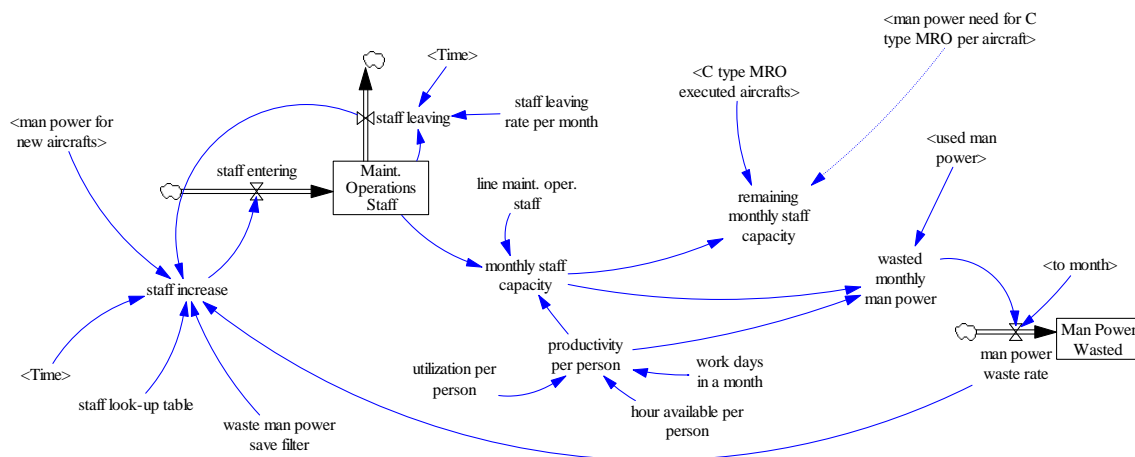


Figure 4.15. MRO Human Resource Management Policy Sub-Model

Passenger capacity sub-model introduces the two important shortfall mechanisms to keep up with the forecasted demand, MRO capacity shortfall and aircraft capacity shortfall. MRO capacity shortfall is triggered when the MRO staff capacity lacks the capability to execute MRO activities of the fleet. This situation causes to lose airworthiness of some aircrafts and they became unable to carry passenger or goods. Aircraft capacity shortfall appears when the fleet seat capacity is not enough to carry the desired forecasted passenger capacity. To solve these situations, recruitment of MRO staff and expanding the aircraft fleet are chosen as business policies respectively. The detailed business flow and formulations are presented at Figure 4.16 and Table 4.8.

Table 4.8. Passenger Capacity Sub-Model Equations

Equation	Unit	Number
A type MRO executed aircrafts=MIN (Potential Aircrafts to Use, potential to end A's)	aircraft	(4.50)
actual aircrafts in use=A type MRO executed aircrafts	aircraft	(4.51)
aircraft capacity shortfall=MAX(0,INTEGER(Monthly aircraft shortage filtering ratio* (demand rate-passengers per month)/(average number of passengers in a flight*average number of flights per aircraft in a month) - MRO capacity shortfall))	aircraft/ Month	(4.52)
C type MRO need per month= INTEGER (total aircrafts * C Type MRO ratio)	aircraft/ Month	(4.53)
Demand Forecast= INTEG (demand rate, 1.04e+007)	Passenger	(4.54)
demand rate=forecast look-up table	Passenger/ Month	(4.55)
flight capacity per month= INTEGER (actual aircrafts in use*average number of flights per aircraft in a month)	flight/Month	(4.56)
forecast look-up table = WITH LOOKUP (Time,([(2003,0)-2025,2e+007]), (2003,1.658e+006),(2004,1.742e+006), (2005,1.989e+006), (2006,2.343e+006),(2007,2.66e+006), (2008,2.953e+006),(2009,3.414e+006),(2010,3.717e+006), (2011,4.353e+006),(2012,5.019e+006),(2013,5.909e+006), (2014,6.759e+006),(2015,7.187e+006),(2016,7.849e+006), (2017,8.272e+006),(2018,8.873e+006),(2019,9.387e+006), (2020,9.981e+006),(2021,1.049e+007),(2022,1.096e+007), (2023,1.133e+007), (2024,1.2e+007), (2025,1.236e+007)))	Passenger/ Month	(4.57)
MRO capacity shortfall= MAX(0, IF THEN ELSE((C type MRO need per month + actual aircrafts in use*to month) > total aircraft MRO desired ratio*total aircrafts*to month , 0 , INTEGER(to month*(total aircrafts-actual aircrafts in use)) - C type MRO need per month))	aircraft/ Month	(4.58)
Passenger= INTEG (passengers per month,1.04e+007)	Passenger	(4.59)
passengers per month=flight capacity per month*average number of passengers in a flight	Passenger/ Month	(4.60)
total aircrafts= Aircrafts at C Type MRO + Potential Aircrafts to Use	aircraft	(4.61)
Total Flights= INTEG (total flights per month, 100000)	flight	(4.62)
total flights per month= flight capacity per month	flight/Month	(4.63)

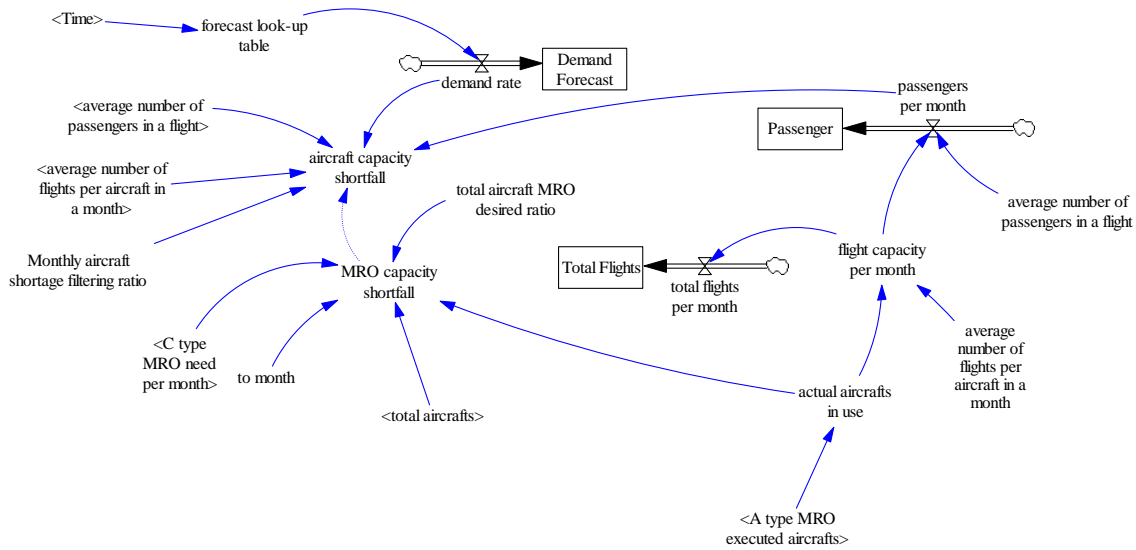


Figure 4.16. Passenger Capacity Sub-Model

MRO cost sub model simply puts forward the cost of all the MRO production. The hourly man power cost includes all the related expenditures regarding MRO tasks. The used man power and its hourly cost together with give the overall MRO operations cost as seen at Figure 4.17 and Table 4.9.

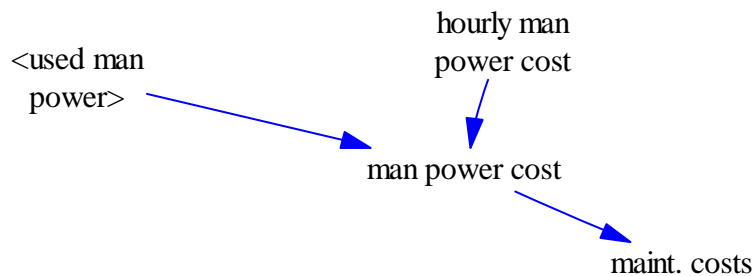


Figure 4.17. MRO Cost Sub-Model

Table 4.9. MRO Cost Sub-Model Equations

Equation	Unit	Number
$\text{maint. costs} = \text{man power cost}$	Dollar/Month	(4.64)
$\text{man power cost} = \text{hourly man power cost} * \text{used man power}$	Dollar/Month	(4.65)
$\text{used man power} = \text{A type MRO executed aircrafts} * \text{man power need for A type MRO per aircraft} + \text{C type MRO executed aircrafts} * \text{man power need for C type MRO per aircraft}$	man*hour/Month	(4.66)

4.4. Validation of the Model

There is a strong dependence between the validity of model and its purpose. The notion of the validity can be seen as “usefulness with respect to some purpose”. This brings forth the question of judgment about the validity of model which directly encapsulates the judgment about the validity of its purpose. Therefore, this judgment is basically introduces the nontechnical, informal and qualitative measures into model validation (Barlas, 1996). Moreover, as stated by (Greenberger, et al., 1976, pp. 70-71), it is almost impossible to validate a model completely. Thus, it may be more appropriate to say “useful,” “illuminating,” “convincing,” or “inspiring confidence” rather than “valid” (Sterman, 2000).

System dynamics modelers have developed various kinds of tests to reveal the flows and enhance the quality of models. The detail of these kinds of tests can be found at almost all text books about system dynamics like (Sterman, 2000). The most common tests are, but not limited to, boundary adequacy, structure assessment, dimensional consistency, parameter assessment, extreme conditions, integration error, behavior reproduction, behavior anomaly, family member, surprise behavior, sensitivity analysis and system improvement (Sterman, 2000). In validation process, it is enough to apply a subset of these tests to be sure about the usefulness of the model to serve to analyze the problem and establish confidence, communication and persuasion among modelers, clients, and other related parties. So, each modeler uses his or her own judgmental criteria about the quality and suitability of a model. All in all, a model is considered as realistic to the degree that it can be clearly comprehended and approved (Sterman, 2000).

For boundary adequacy test, the important feedback loops, endogenous and exogenous variables and equations are formed as explained in previous sub-sections. There are also other important variables and feedback loops that may be originated from the other departments or the factors of the company like finance during the procurement of new aircrafts and the recruitment of MRO staff. But, for the sake of simplicity, understandability and their negligible effects for the purpose of model, they are omitted from the model.

For the structure assessment test, it is important to put forward how in reality the model represents the physical structure of the system relevant to the purpose (Sterman, 2000). Thus, the level of aggregation and compliance to the real physical system such as conservation laws are investigated on the casual diagram, stock and flow diagram, and on the inputs, outputs and units of equations. Violations of the physical laws must be eliminated from the model such as conservation of matter or energy (Sterman, 2000). While doing these checks, levels are controlled to be sure of not being negative as physical quantities at the levels (stocks) of the stock and flow diagram cannot be negative. The more detailed sub-portions of the model is aggregated later to make it simple by preserving overall structure and functions.

The dimensional consistency test is executed with Vensim Unit Check capability and by examining the equations of the model. This test is very useful to reveal the flaws in the construction of the model (Sterman, 2000).

Parameter assessment is another important validation step in modeling and there are various methods such as ordinary least squares, maximum likelihood and Kalman filtering if numerical data exists. Even though, the existence of numerical data, expert opinions and judgments are also important factors during the estimation of the parameters (Sterman, 2000). The historical data and expert judgment are used altogether to estimate the values of parameters used in this study whose list are presented at Table 4.4.

Extreme conditions test is a good way to observe the behavior of the model in rare conditions. If model shows the expected functionality in these rare conditions, it can be thought as a good sign to trust to the model. In order to test this, some extreme values are applied in the model and the behaviors are observed.

The following is a sample for this purpose in that the initial value of MRO staff is zeroized, the real MRO staff capacity removed and the behaviors in the Figure 4.18, Figure 4.19, Figure 4.20 and Figure 4.21 are observed.

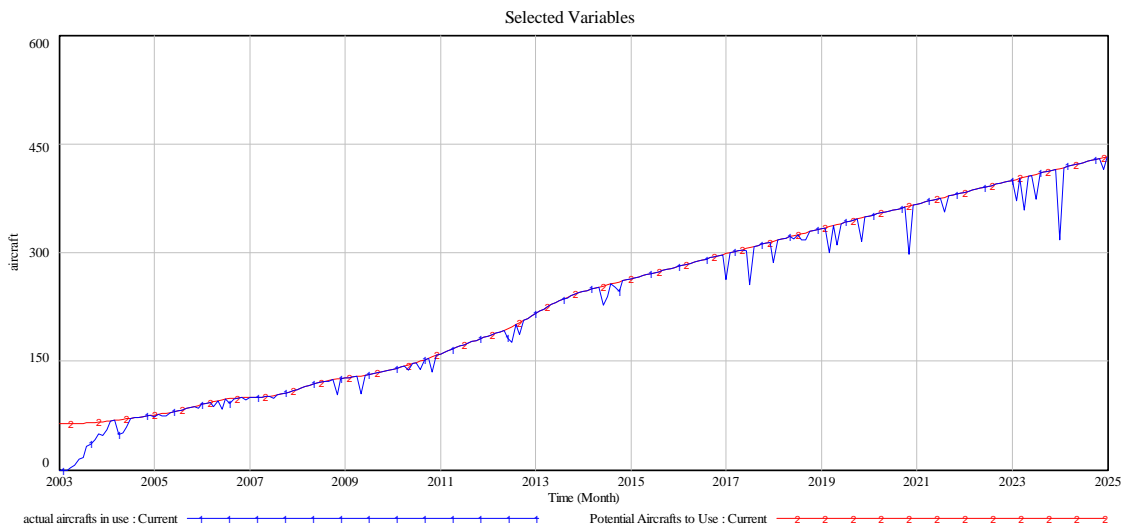


Figure 4.18. Initial MRO Staff Zeroized: Aircrafts in Use

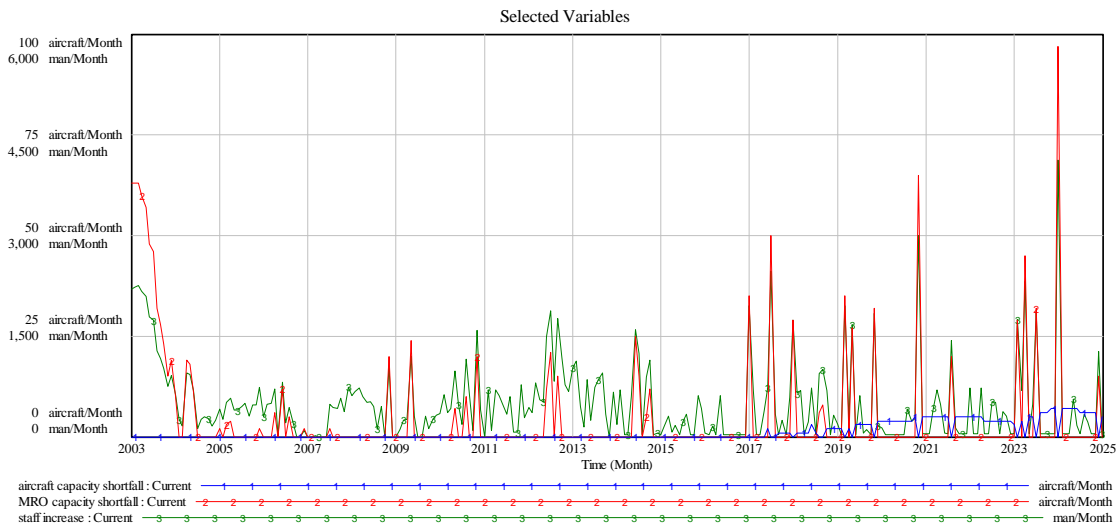


Figure 4.19. Initial MRO Staff Zeroized: MRO Staff Capacity Shortfall, MRO New Staff, Aircraft Capacity Shortfall

Figure 4.18 states that if MRO facility is initially lack of the full capability, even though airline has aircrafts, the available aircrafts will lose the airworthiness and will not serve to carry the passengers at the initial years until some kind of MRO capability sustained. Later, the model tries to reach equilibrium to maintain the aircrafts by introducing high capacity of MRO operations staff.

Figure 4.19 states that as the MRO facility is initially lack of the full capability, MRO capacity shortfall behavior is observed and model recruits lots of MRO staff.

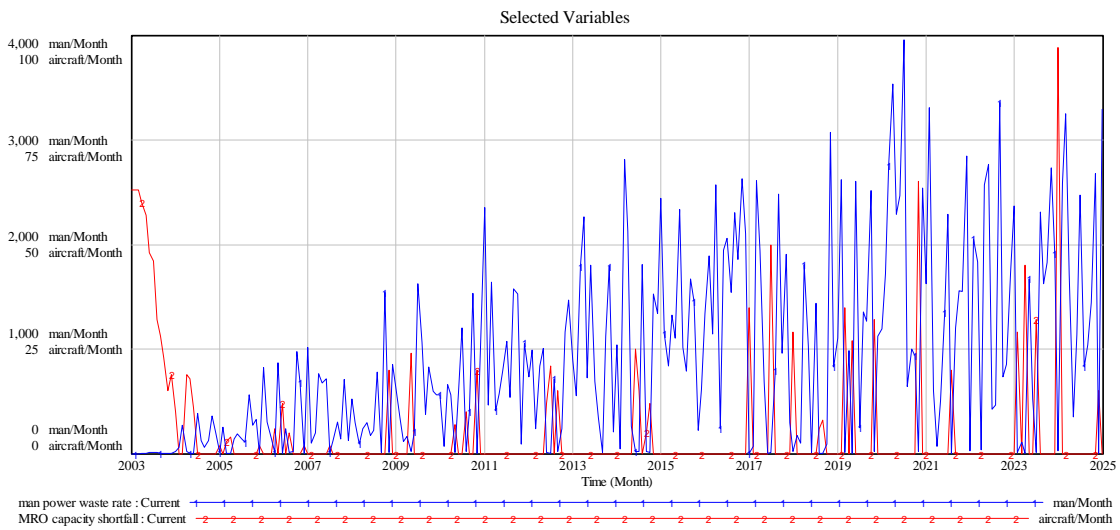


Figure 4.20. Initial MRO Staff Zeroized: MRO Staff Capacity Shortfall, MRO Staff Waste

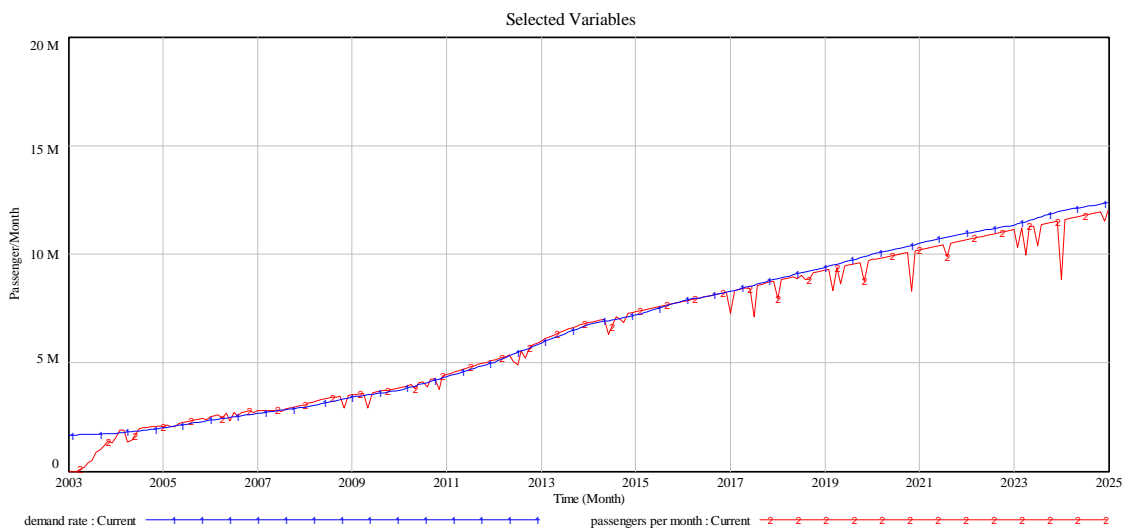


Figure 4.21. Initial MRO Staff Zeroized: Demand and Actual Passengers

Figure 4.20 states that as the MRO facility is initially lack of the full capability, MRO capacity shortfall behavior is observed and as a result the man power in hand is fully utilized and not wasted approximately until 2005.

Figure 4.21 shows that if the MRO facility is initially lack of the full capability, even though airline has enough aircrafts, MRO facility lose its capability to sustain the airworthiness of all those aircrafts and airline will not carry the intended number of passengers in early years.

The next scenario is the opposite of the previous one in that the number of initial staff MRO is very high whose sample figures are Figure 4.22 and Figure 4.23.

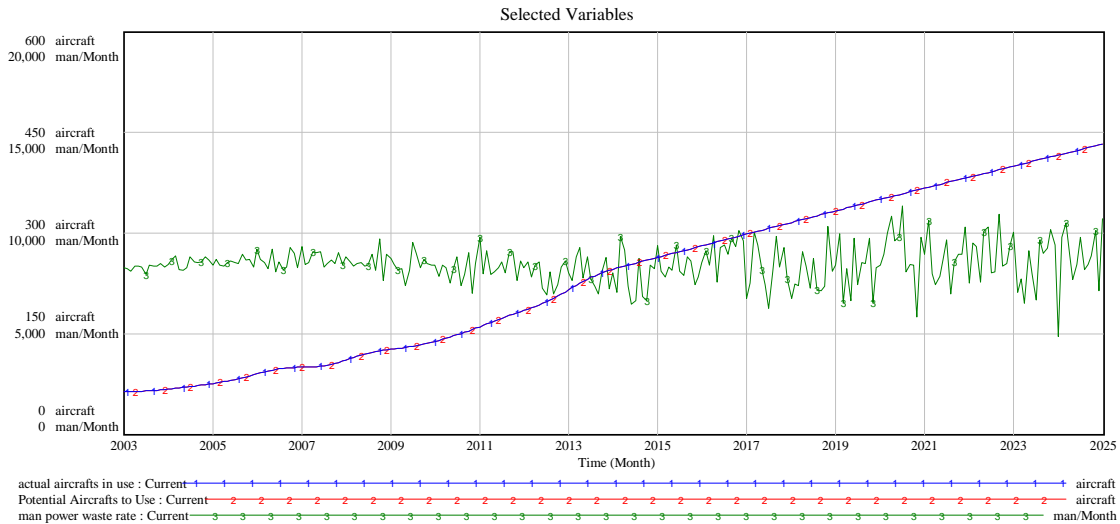


Figure 4.22. Initial MRO Staff High: Potential and Airworthy Aircrafts to Use and Man Power Waste

Figure 4.22 states that if MRO facility has more capacity than needed, all the MRO needs of the aircrafts will be handled in time but, a significant portion of this MRO capacity will be wasted.

Figure 4.23 states that if MRO facility has more capacity than needed, there will be no MRO capacity shortfall initially and thereafter.

In an extreme condition scenario where model start with zeroized aircrafts as seen in Figure 4.24, the model tries to increase the size of the aircraft fleet to carry the desired passengers.

Behavior Reproduction Tests are performed by point-by-point comparison of the real data series with the model outputs over a time horizon. For this purpose, some measures such as R^2 , the coefficient of determination, the mean absolute error, MAE; mean absolute percent error, MAPE; mean absolute error as a percent of the mean, MAE/Mean; and (root) mean square error, (R)MSE, are used (Sterman, 2000).

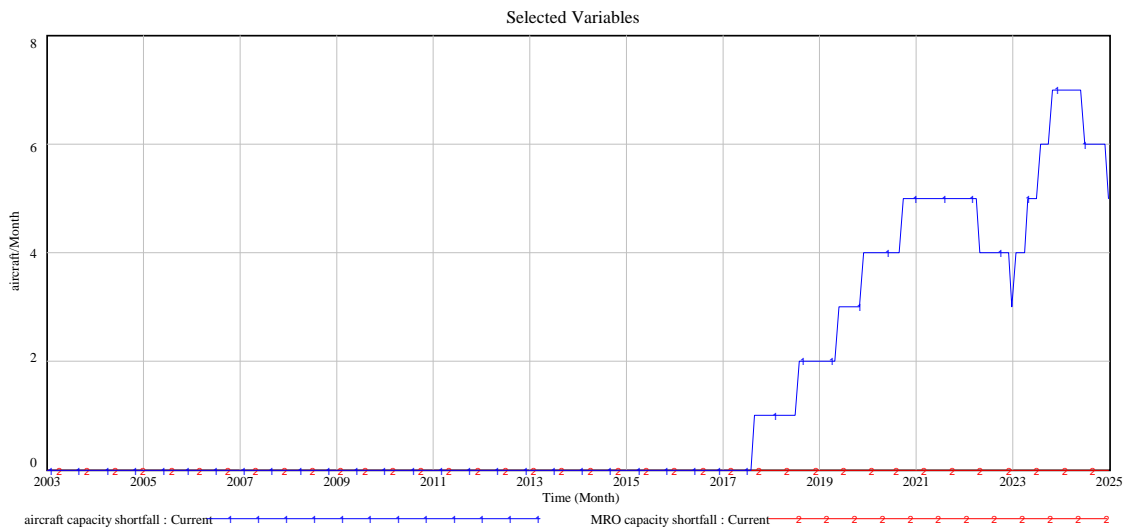


Figure 4.23. Initial MRO Staff High: Aircraft Capacity Shortfall and MRO Capacity Shortfall

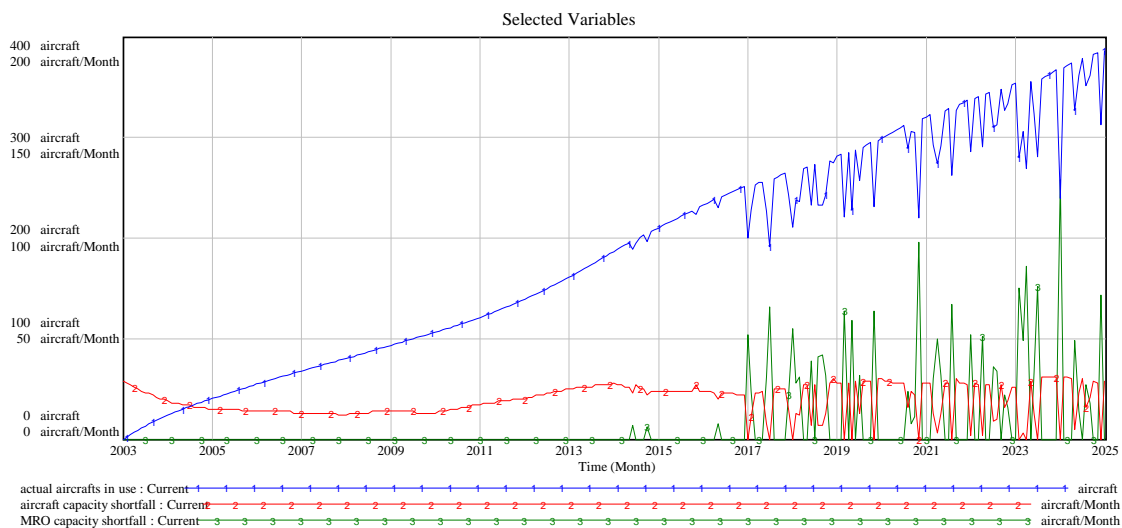


Figure 4.24. Initial Aircraft Zeroized : Available Aircrafts, Aircraft Capacity Shortfall and MRO Capacity Shortfall

To check the behavior reproduction, the model output is compared with the real data as seen at Figure 4.25 and Figure 4.26 whose data are total flight number and total number of passengers respectively. The model actually tries to catch up with the forecasted demand and regulates the flight and MRO staff capacity to do so. There was an economical recession during years 2007 and 2008, and the downgrade effects of this can be seen at Figure 4.26. Even though the flight capacity seems steady at those years, due to the low load factor, fewer passengers are carried.

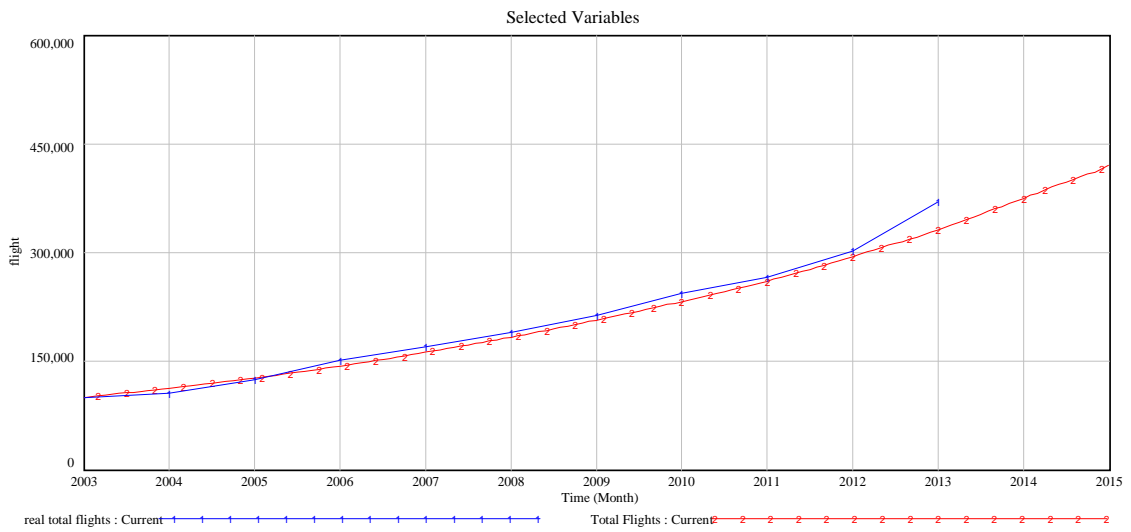


Figure 4.25. Total Flight Number Capacity Comparison

MAPE for flights is approximately 7% as seen at Figure 4.25.

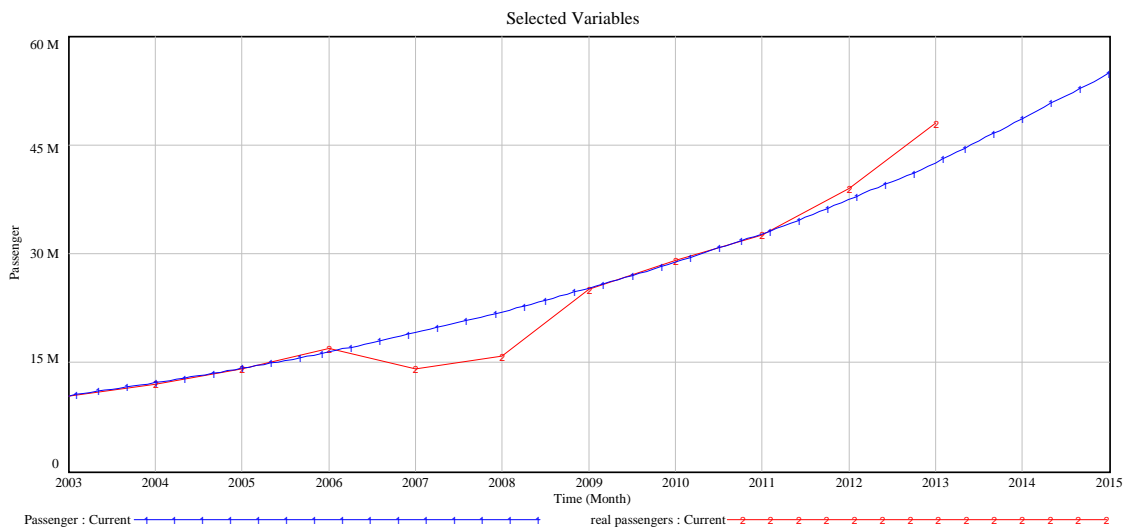


Figure 4.26. Total Number of Passenger Comparison

MAPE for passenger is approximately 10% as seen at Figure 4.26.

5. RESULTS AND DISCUSSIONS

The MRO activities of Turkish Airlines fleet are handled by the both Turkish Technic and Turkish HABOM Maintenance Departments which are the subsidiaries of Turkish Airlines Companies. Turkish Airlines ordered approximately 200 aircrafts lately and try to increase its share in the airline market. This raises concerns about how the aircraft fleet growth will affect the productivity of the Turkish Airline MRO Departments and needed new resource to be incorporate into MRO Operations Staff to cope with this new situation.

Another important factor directly affecting the MRO department is the number and the timing of aircrafts that is going to join the aircraft fleet. New aircrafts will have impact on the increase of number of passengers and extra burden on the MRO facility. Thus, different combination of sizing and timing of new aircrafts and its effects on MRO operations have to be investigated.

To evaluate these situations, two scenarios are proposed respectively, scenario 1 and scenario 2.

5.1. Scenario 1 : The Varying MRO Operations Volume : Under Low, Normal and High Load

The MRO operations volume is changed by taking the variable A type MRO man power at its minimum and maximum levels. The minimum level is the approximately 100 man x hour / week and labeled as “Low MRO Load” in the figures. On the other hand, the maximum level is approximately 500 man x hour / week and labeled as “High MRO Load” in the figures. For normal level, a random value is taken between 100 and 500 100 men x hour / week. These minimum and maximum levels can be thought as a confidence interval to portray the optimistic and pessimistic work load expectation. The same approach can be tested for the C type MRO load. For this scenario, the C type MRO man power and all the other variables are kept unchanged as explained in previous section. In the scenario, the historical data is used until the year 2014. It is assumed that aircraft fleet will get 20 aircrafts per year after the year 2013.

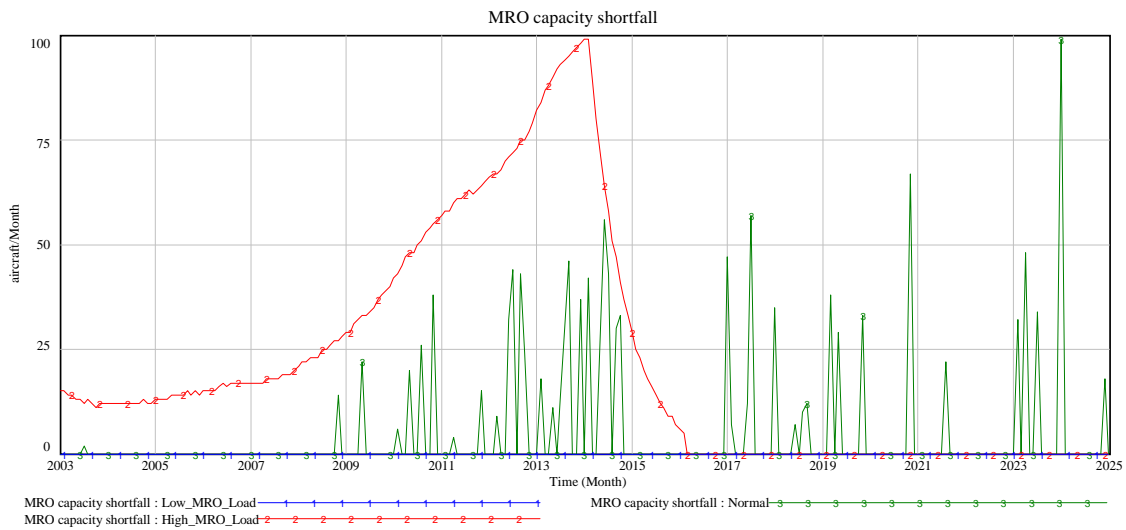


Figure 5.1. MRO Shortfall Monthly Comparison

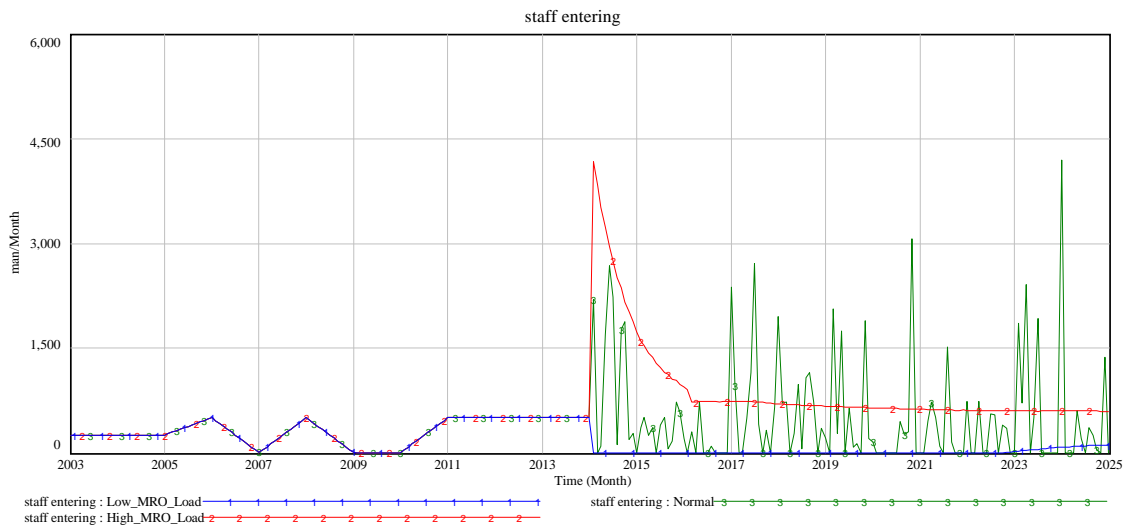


Figure 5.2. Monthly MRO Staff Recruitment Comparison

As seen at Figure 5.1, due to the heavy MRO load, the MRO facility is lack of enough capacity to sustain the airworthiness of all the available aircrafts. This behavior can be seen at the figure with a highly elevated MRO capacity shortfall. The model uses the historical MRO staff and aircrafts until the year 2014. That is why, you can see an elevated MRO capacity shortfall until this year for high MRO load. Following the year 2013, the model balances this shortage by introducing a large number of MRO operations staff.

The introduction of this new MRO staff can be observed in Figure 5.2 on monthly basis. For the low MRO load, there is almost no need to recruit MRO staff as the available MRO staff can handle the MRO operations. This behavior also can be seen at Figure 5.3 with no slope at related line, which is numbered as 1.

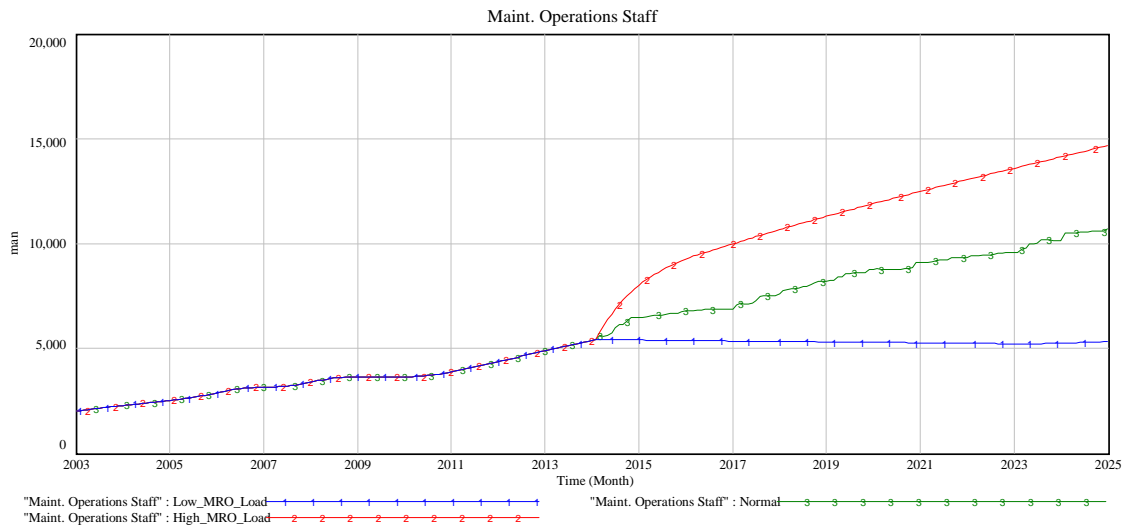


Figure 5.3. Total MRO Operations Staff Comparison

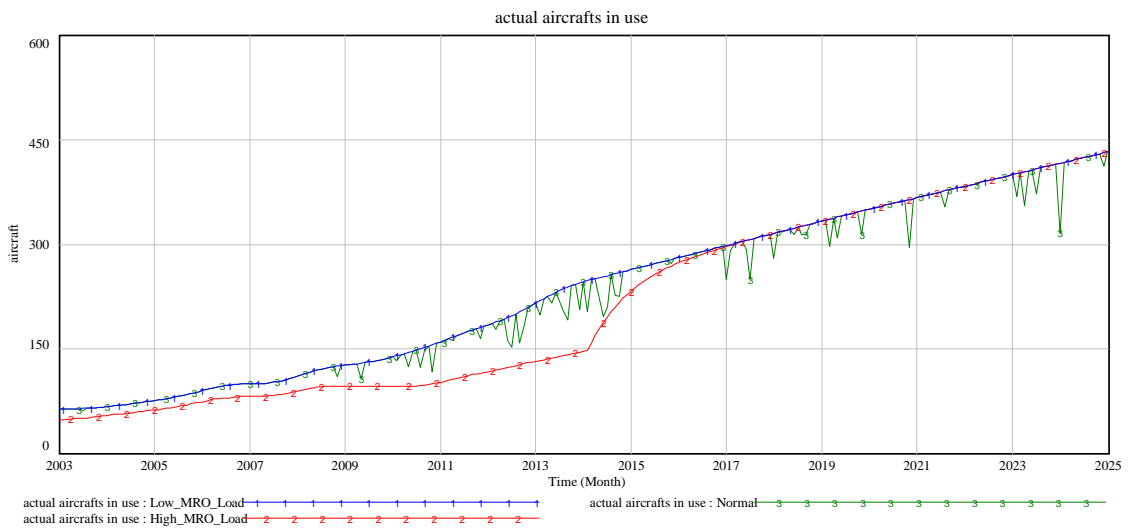


Figure 5.4. Aircrafts in Service Monthly Comparison

When the recruitment of MRO staff sketched on a cumulative manner as seen Figure 5.3, the optimistic, the regular and the pessimistic MRO operations staff can be clearly spotted. The effects of adoption of these MRO recruitment policies end up with the

number of airworthy aircrafts or the number of the passengers carried as seen at Figure 5.4, Figure 5.5 and Figure 5.6 respectively. The y-axis represents the MRO department production as the airworthy aircrafts in Figure 5.4. As seen at Figure 5.4, when MRO load is low, represented as line number 1, there is enough MRO capacity to handle the MRO needs of all the aircrafts. This enables airline to use all the available seat capacity. On the other hand, when MRO load is high, represented as line number 2, MRO facility is unable to handle the MRO needs of all aircrafts and a significant portion of the aircrafts wait on the ground. In this high work load case, airline carrier cannot use all the available seat capacity. The number of aircrafts, until 2016, represented by this line is lower than the other two lines, low and normal work load.

There is a behavior overlap with the number of airworthy aircrafts and the seat capacity, in which they are directly related, as seen at Figure 5.5 and Figure 5.6. They follow the same pattern.

After the year 2013, the model introduces the recruitment of additional MRO operations staff. That is why, the heavy MRO staff airworthy aircraft shortages disappear as seen at Figure 5.4. But, on the other hand, keep in mind that additional MRO staff also bring financial burden to the airline company.

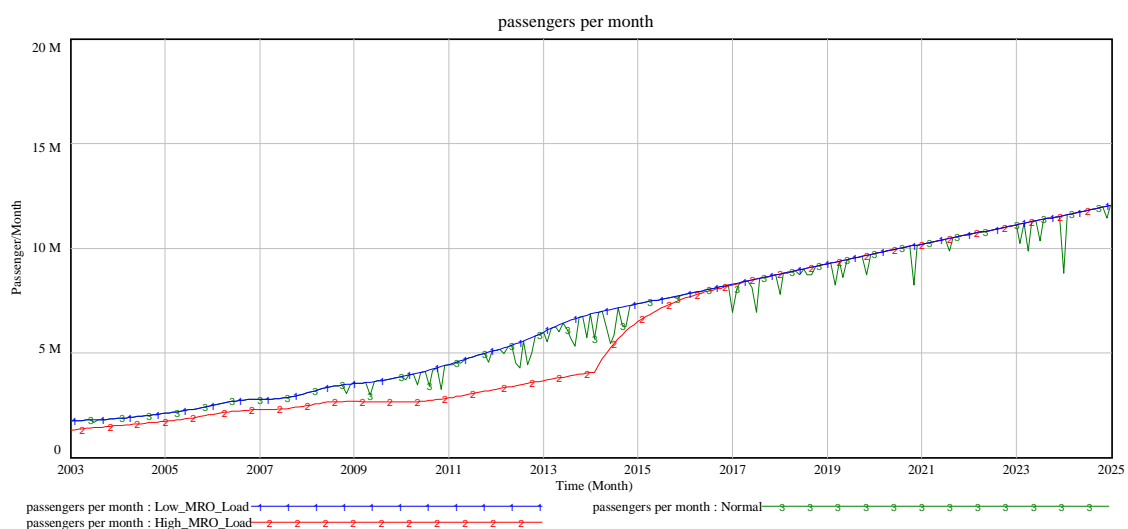


Figure 5.5. Passenger Monthly Comparison

The more MRO operations tasks may mean less airworthy aircrafts if the airline MRO facility does not have enough capacity to handle those tasks. This will cause to reduce

the number of potential passenger and to lose revenues. This behavior is observed in the Figure 5.5 and Figure 5.6 as fewer passengers.

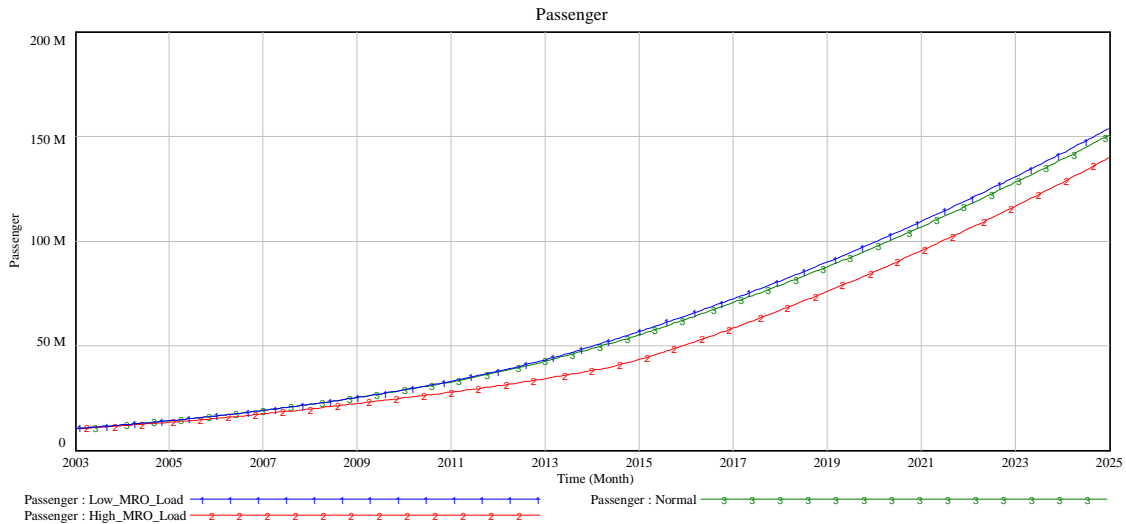


Figure 5.6. Total Passenger Comparison

The balancing of the adequate number of MRO operations staff and the utilization of this staff is a challenging task. The excessive MRO staff is a financial burden, but the lack of enough MRO staff is also indirectly another financial burden as fewer airworthy aircrafts in service. So it is sometimes inevitable not to waste the man power of MRO capacity when MRO facility faces light work load tasks. The wasted or spare man power for MRO facility is depicted monthly and cumulatively at Figure 5.7 and Figure 5.8 respectively. This spare force can be thought of as insurance during the unexpected extra ordinary situations or it can also be outsourced to earn extra revenue. During the low MRO needs, depicted as line 1 at Figure 5.7 and Figure 5.8, a good portion of man power capacity wait idle. On the other hand, when confronted with heavy MRO load, depicted as line 2 at Figure 5.7 and Figure 5.8, almost all MRO staff capacity is used for maintenance. For the normal work load, depicted as line 3, no specific overcapacity pattern is observed except the amplitude increase of the wavy pattern.

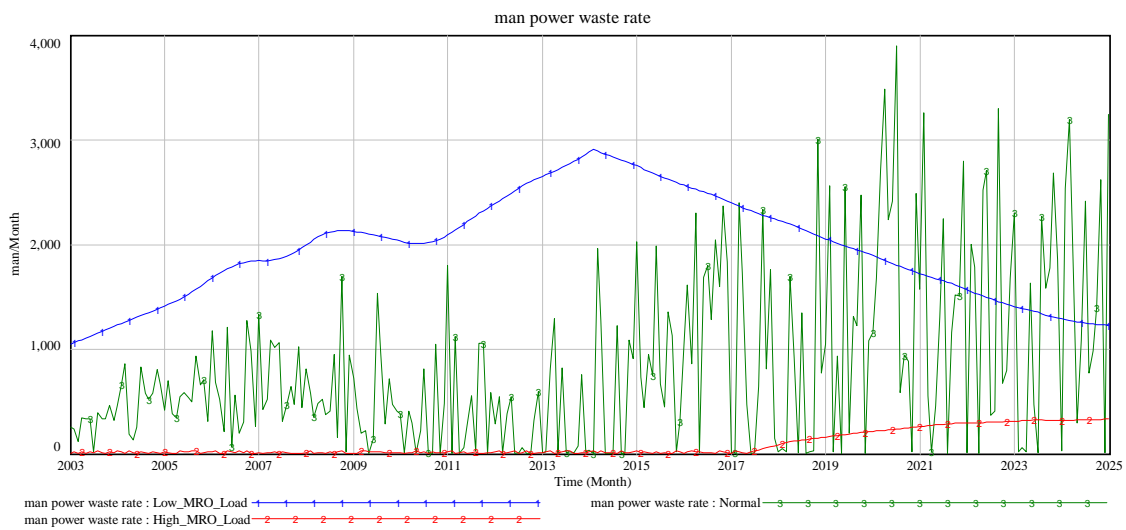


Figure 5.7. Wasted Man Power Monthly Comparison



Figure 5.8. Total Wasted Man Power Comparison

Figure 5.7 and Figure 5.8 also give idea about the productivity and the utilization of the MRO facility. The higher the slope of lines, the more man power waste (see Figure 5.8). When the MRO work load is low, a significant amount of resource seems excess as shown with line 1. On the other hand, in case of high MRO work load, almost all the resources seem to be used efficiently as shown with line 3.

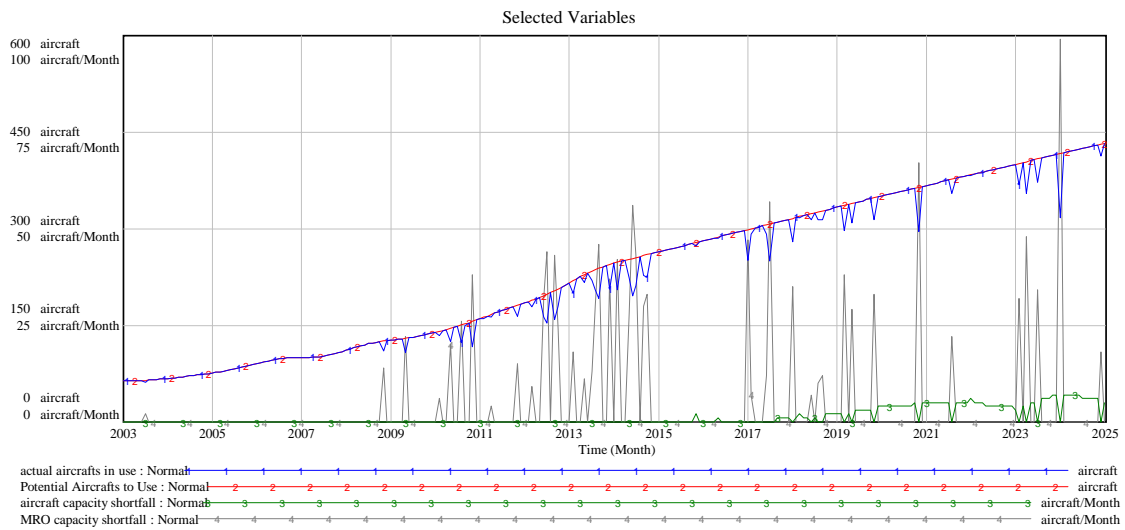


Figure 5.9. Overall Model Response

When the model simulated with the default settings, the system tries to reach equilibrium as seen at Figure 5.9.

Based on the simulation run in this scenario, the human resource need of MRO department can be foreseen for the next decade considering the optimistic/pessimistic approaches. In order to preserve the sustainability of the company, these resource need has to be taken into account. Again, the spare resource can be used to give service to the third party airline MRO operations for extra revenue for the company.

When the Figure 5.9 examined closely, normally all potential aircrafts, showed with line 2, should be in service. But due to the inadequate MRO capacity, the MRO needs of some aircrafts cannot be handled and as a result a gap is observed between actual aircrafts in use and potential aircrafts to use. This behavior is depicted in the figure with lines 1 and 2. Actual aircrafts in use is the output of normal system behavior and can be thought as the number of available aircrafts to use. The gap mentioned here is the result of inadequate MRO capacity. Model detects this shortfall and tries to reach equilibrium by incorporating new resources. This is the behavior between lines 1 and 4. The notches on these lines are in opposite direction as expected. The size of aircraft fleet is normally big enough to carry the forecasted seat demand as depicted with line 3. But after the year 2018, there some small notches on this line which means that fleet seat capacity is short to meet the forecasted seat capacity. The model mimics the real system behavior as expected.

5.2. Scenario 2 : The Different Aircraft Procurement Policies

In another scenario, the behavior of the system was tested with aggregated fleet expansion. In the previous scenario, aircraft fleet expanded with 20 aircrafts per year as seen at Table 5.1. For this scenario, aircraft fleet expansion was assumed to be planned as in Table 5.2.

Table 5.1. The Aircraft Fleet Expansion Policy in the Main Scenario

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	
Aircrafts	0	8	10	20	-1	25	7	18	27	23	42	
Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Aircrafts	20	20	20	20	20	20	20	20	20	20	20	20

For this scenario, the total number of aircrafts after the year 2013 is depicted in the Figure 5.10. The shape of the graph is a step function. This means sudden overload for MRO facility and instant passenger capacity expansions. Another issue may be the passenger seat capacity shortfalls in the intervals of no new aircrafts.

Table 5.2. The Aircraft Fleet Expansion Policy after the Year 2013

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	
Aircrafts	0	8	10	20	-1	25	7	18	27	23	42	
Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Aircrafts	0	0	60	0	0	60	0	0	60	0	0	60

When the Figure 5.10 and Figure 5.11 examined together, during the aircraft not expanded, flat period in total aircraft graph, aircraft capacity shortages are observed and as a result, the passenger seat capacity remains the same and not meets the forecasted passenger demand as seen at Figure 5.12 and Figure 5.13. The big waves in the Figure 5.11 regarding the aircraft seat capacity, line 1, represents these seat capacity shortages. Keep in mind that these seat capacity shortages are caused mainly by inadequate fleet size and MRO capacity does not have big impact during these periods.

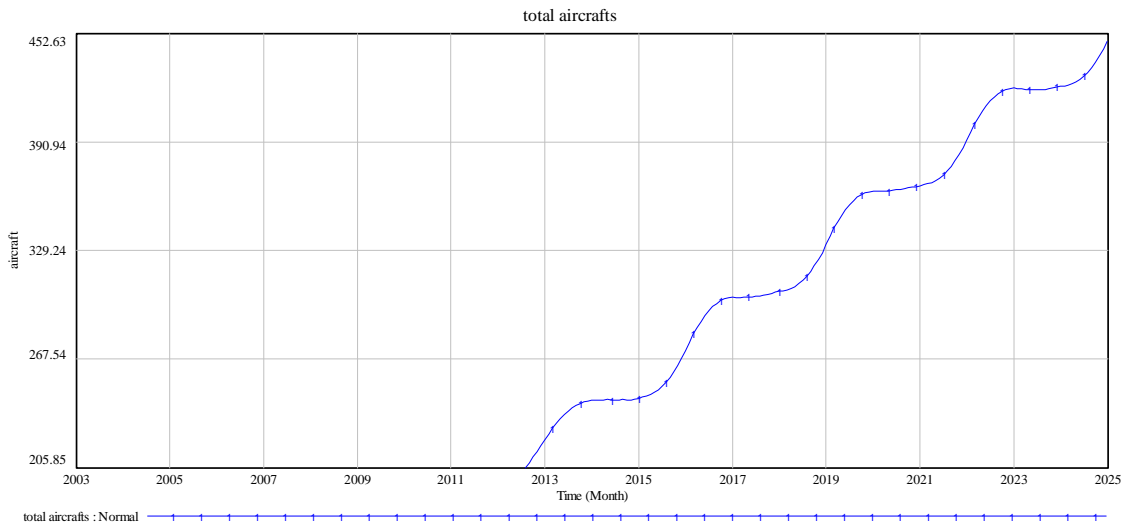


Figure 5.10. The Total Aircraft Fleet Expansion

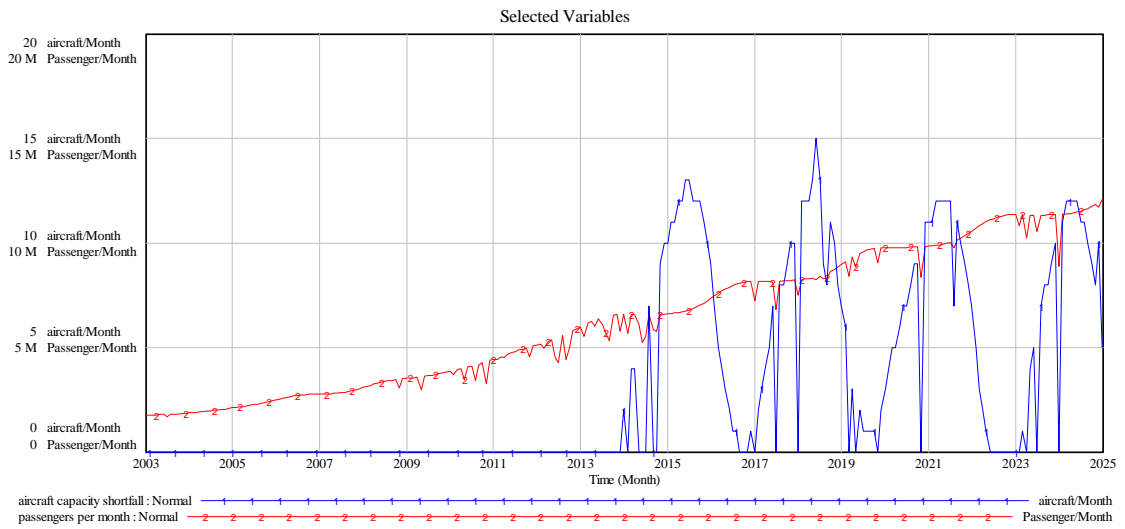


Figure 5.11. Aircraft Capacity Shortfall and Monthly Passenger Size

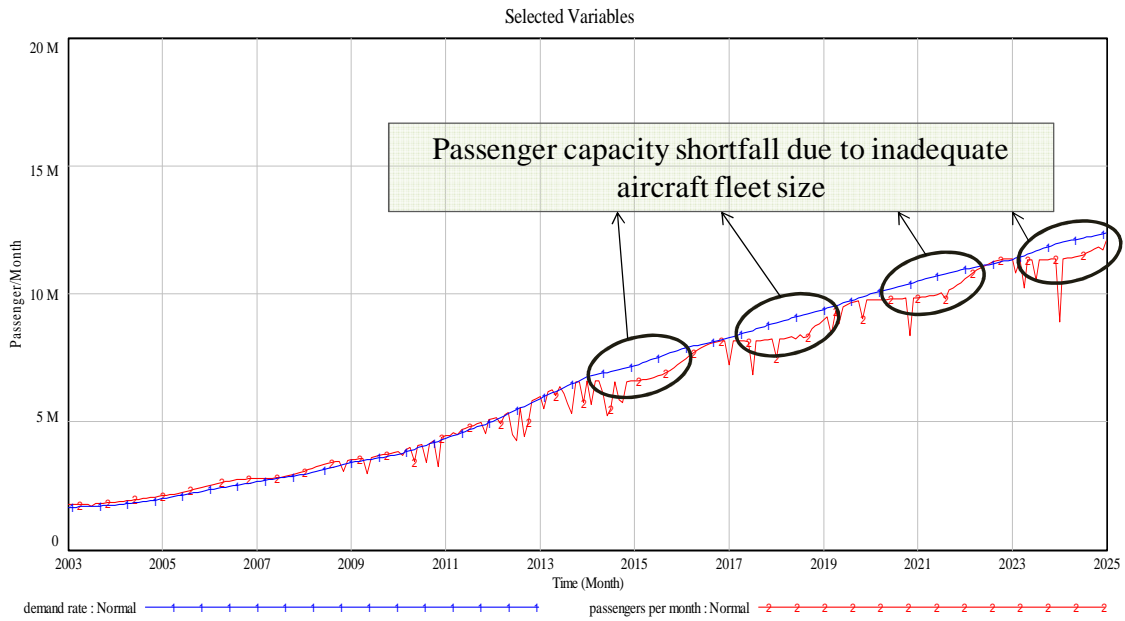


Figure 5.12. Monthly Comparison of Passenger with Forecast and Model Output

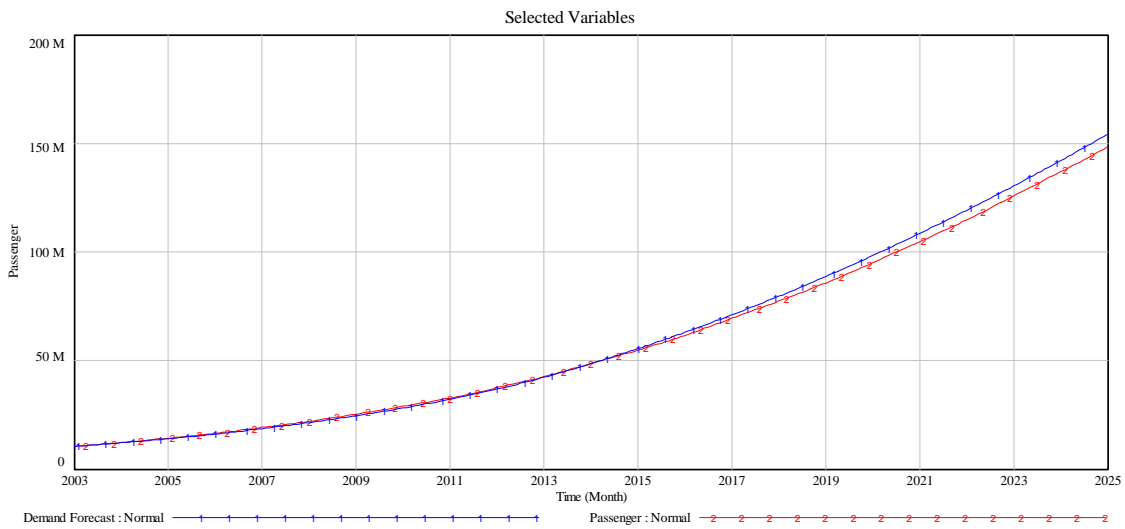


Figure 5.13. Comparison of Passenger with Forecast and Model Output

The highly aggregated aircraft fleet expansion introduces the highly aggregated recruitment of MRO operations staff to answer the MRO tasks of those aircrafts as seen at Figure 5.14 (look at line 4) within the same time period. So, almost all potential number of aircrafts can be used for service due to this new MRO operations staff. The result of this can be observed at the graph as a strong matching between ‘potential aircrafts to use’ and ‘actual aircrafts in use’.

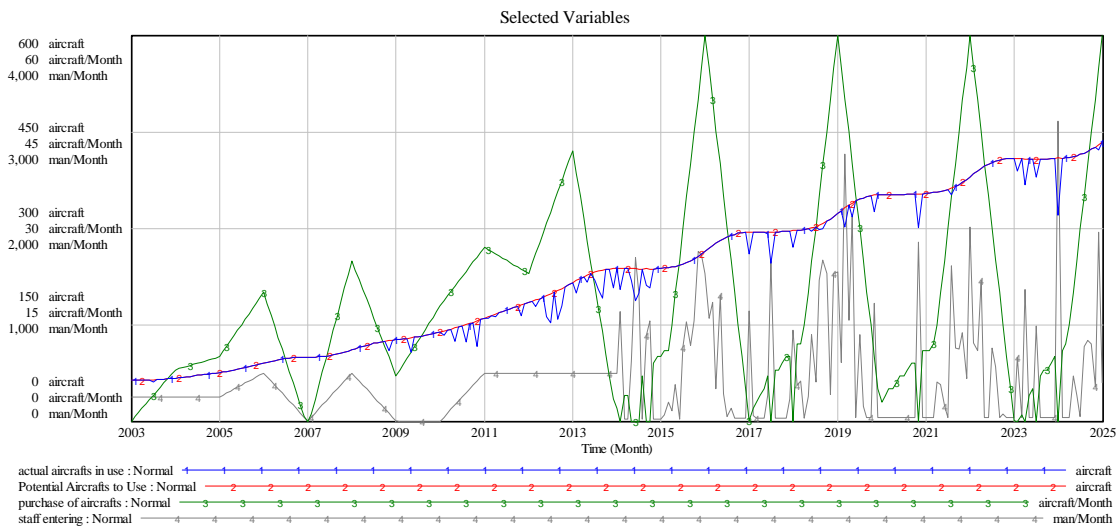


Figure 5.14. The Recruitment of Additional MRO Staff to Meet MRO Operations of New Aircrafts

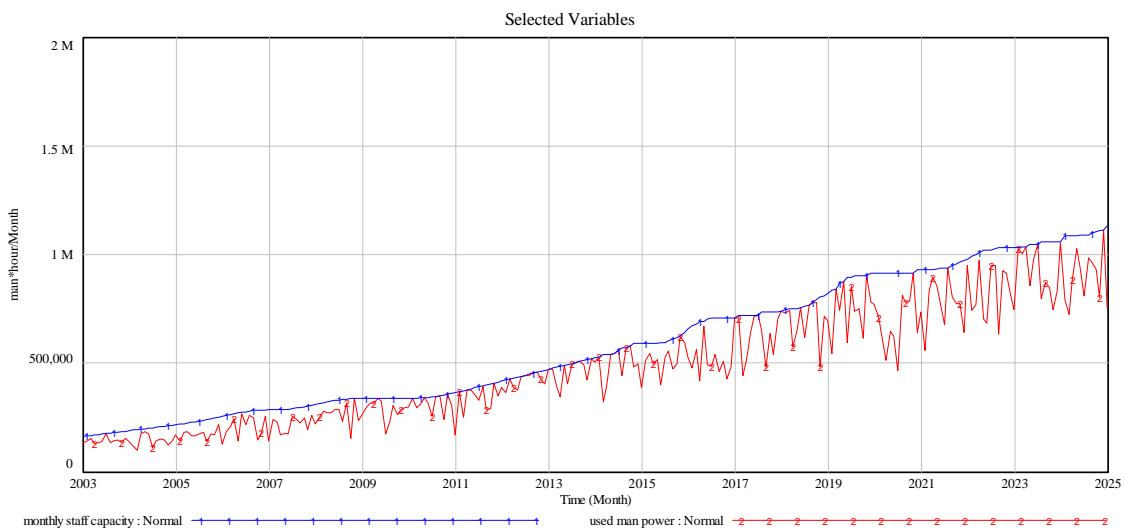


Figure 5.15. Used MRO Operations Staff Capacity

As the MRO operations staff salaries are important expenditures for the airline companies, it is a reasonable action to try to keep them at minimum level. On the other hand, when aircraft fleet has unexpected high amount of MRO occurrences, the company will have a lot of aircrafts that lose their airworthiness due to inadequate MRO capacity. So, the MRO facility must have enough additional MRO capacity to meet these kinds of events. In this view, Figure 5.15 shows the monthly MRO staff capacity and how much of this capacity is used. There are gaps between two lines at the graph. This gap can be considered as waste or spare as seen at Figure 5.16. It may be a good

option to outsource this capacity to earn additional revenues for the company during the low levels of MRO operations of own company.

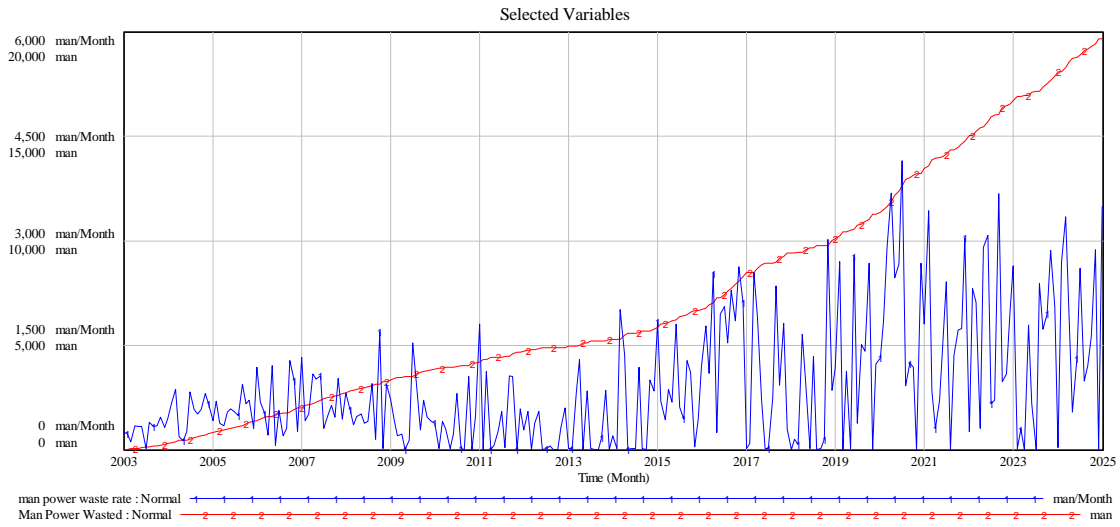


Figure 5.16. Wasted or Spare Man Power

When the Figure 5.16 is examined, there is trend of increased variability at the amplitude of the wasted/spare man power when the number of aircrafts is increased. So, it may be a more challenging task to decide how many MRO operations staff to employ.

5.3. Discussions and Managerial Applications

There are lots of airline operations including, but not limited to, flight scheduling, fleet assignment, aircraft routing, crew scheduling, manpower planning, revenue management, fuel management systems, airline irregular operations, gate assignment, aircraft boarding strategy, airline operations and scheduling (Bazargan, 2010). The aircraft maintenance, repair and overhaul (MRO) activities hold an important place in all these airline operations. The cost of MRO activities in its pure nature is very significant and around 10% in all cost drivers (Merkert, 2010) (Von Beuningen, 2014). Additional costs and revenue losses may be observed as result of unsatisfactory management of MRO activities.

When the aerospace industry is examined, the life span of aircrafts is usually around 30 years (Airbus, 1999). So, aircrafts need lots of maintenance services in these years. Thus, for aerospace industry, much of the profit is not acquired from the sale of the aircraft, but from the maintenance of them throughout the life span (Lee, et al.,

2008)(Dutta & Wolowicz, 2005). Majority of the vehicle life cycle cost is caused by the operations and support (maintenance and logistics) activities (Iwata & Mavris, 2013). That is why, major OEMs like Boeing and Airbus try to capture the biggest market share in MRO.

There is tightly coupled interaction between the maintenance activities and the human resources function. The capacity and capability of maintenance is mainly based on available human resources and the equipment. The number of people, level of knowledge and skill as a whole impacts the productivity of the maintenance department. Overtime or high workload to increase maintenance capacity causes to lower the productivity because of factors such as fatigue and attention disorder. Moreover this policy in the long run, due to the greater personnel turnover, may elevate rookies' ratio over experts, which in turn could result in reduction in maintenance capacity and more training costs (Bivona & Montemaggiore, 2010).

The MRO activities of Turkish Airlines fleet are handled by the both Turkish Technic and Turkish HABOM Maintenance Departments which are the subsidiaries of Turkish Airlines Companies. Turkish Airlines ordered approximately 200 aircrafts lately and try to increase its share in the airline market. New aircrafts will have impact on the increase of number of passengers and extra burden on the MRO facility. Another important factor directly affecting the system is the number and the timing of aircrafts that is going to join the aircraft fleet. Thus, different combination of sizing and timing of new aircrafts will have varying effects on MRO operations. This study investigated how the aircraft fleet growth affected the productivity of the Turkish Airline MRO Departments and proposed new MRO Operations Staff incorporation plans to cope with this new situation.

It is important to note that while procuring the new aircrafts, MRO department maintenance capacity has to be increased and improved in order to meet MRO need of the new aircrafts. If not, some portion of the aircrafts will lose their airworthiness and wait on the ground idly without bringing any revenue to the company and moreover, causing additional expenses.

MRO operations have direct impact on the available number of airworthy aircrafts and the fleet seat capacity. The airline companies have to take into account the MRO operations needs of the existing and new aircrafts to sustain a profitable airline fleet. The most important and challenging factor is to decide on the number of MRO operations staff to employ as the variability of MRO operations work load is stochastically very high. Another important factor is the cost-revenue trade-off between hiring MRO operations staff and integration of new aircrafts. If you hire more MRO operations staff than needed then it brings extra costs. If you hire less than needed then you may lose revenue due to the unused flight seat capacity which caused by inadequate MRO capability. After setting up a certain degree of confidence level, this number can be decided based on simulation results. It is also inevitable to waste the some portion of this MRO operations staff. The human resource waste can be thought as an insurance during heavy MRO operations and might also be leased to give service to third party airlines during light MRO work load of own airline.

The aircrafts' MRO operations can also be outsourced to the other MRO departments. But it raises the risks of losing not only the maintainers' skills but also the company's know-how. Additionally, contracting out the maintenance activities bring burden of outsourcing costs. Firing of the spare MRO operations staff may not be an option as it would introduce the problems with unions and local laws (Bivona & Montemaggiore, 2010).

The THY managers can benefit from the model to decide the required number of MRO operations staff and aircraft fleet seat capacity to meet the forecasted demands. Aviation MRO department usually needs skilled and trained staff, so management has to consider the training needs in advance while hiring new MRO staff.

6. CONCLUSIONS AND FUTURE WORK

6.1. Conclusions

The aircraft maintenance, repair and overhaul (MRO) activities hold an important place in airline operations. The cost of MRO activities in its pure nature is very significant and around 10% in all cost drivers (Merkert, 2010)(Von Beuningen, 2014). Additional costs and revenue loses may be observed as result of unsatisfactory management of MRO activities.

When the aerospace industry is examined, the life span of aircrafts is usually around 30 years (Airbus, 1999). So, aircrafts need lots of maintenance services in these years. Thus, for aerospace industry, much of the profit is not acquired from the sale of the aircraft, but from the maintenance of them throughout the life span (Lee, et al., 2008)(Dutta & Wolowicz, 2005). Majority of the vehicle life cycle cost is caused by the operations and support (maintenance and logistics) activities (Iwata & Mavris, 2013). That is why, major OEMs like Boeing and Airbus try to capture the biggest market share in MRO.

There is tightly coupled interaction between the maintenance activities and the human resources function. The capacity and capability of maintenance is mainly based on available human resources and the equipment. The number of people, level of knowledge and skill as a whole impacts the productivity of the maintenance department. Overtime or high workload to increase maintenance capacity causes to lower the productivity because of factors such as fatigue and attention disorder. Moreover this policy in the long run, due to the greater personnel turnover, may elevate rookies' ratio over experts, which in turn could result in reduction in maintenance capacity and more training costs (Bivona & Montemaggiore, 2010).

The MRO activities of Turkish Airlines fleet are handled by the both Turkish Technic and Turkish HABOM Maintenance Departments which are the subsidiaries of Turkish Airlines Companies. Turkish Airlines ordered approximately 200 aircrafts lately and try to increase its share in the airline market. New aircrafts will have impact on the increase of number of passengers and extra burden on the MRO facility. Another important factor directly affecting the system is the number and the timing of aircrafts that is

going to join the aircraft fleet. Thus, different combination of sizing and timing of new aircrafts will have varying effects on MRO operations. This study investigated how the aircraft fleet growth affected the productivity of the Turkish Airline MRO Departments and proposed new MRO Operations Staff incorporation plans to cope with this new situation.

This study mainly focused on developing a system dynamics model for Turkish Airline MRO Department MRO operations. There are several system dynamics studies in the literature focused on airline operations but the MRO operations are almost neglected in them. To the best of author(s) knowledge, this is the first system dynamics study focusing on the interactions among aviation MRO Department and other airline operations.

The developed system dynamics model presented valuable opportunities to test various MRO operations workload and aircraft fleet expansion policies in the modeling virtual world. The model can easily be used as a learning laboratory by changing various parameters and testing different policies. Such a trial is presented in the previous section by changing MRO operation work load (pessimistic, normal and optimistic) and by adopting different aircraft fleet expansion policies. It is important to note that while procuring the new aircrafts, MRO department maintenance capacity has to be increased and improved in order to meet MRO need of the new aircrafts. If not, some portion of the aircrafts will lose their airworthiness and wait on the ground idly without bringing any revenue to the company and moreover, causing additional expenses.

It is found that MRO operations have direct impact on the available number of airworthy aircrafts and the fleet seat capacity. The airline companies have to take into account the MRO operations needs of the existing and new aircrafts to sustain a profitable airline fleet. The most important and challenging factor is to decide on the number of MRO operations staff to employ as the variability of MRO operations work load is stochastically very high. Another important factor is the cost-revenue trade-off between hiring MRO operations staff and integration of new aircrafts. If you hire more MRO operations staff than needed then it brings extra costs. If you hire less than needed then you may lose revenue due to the unused flight seat capacity which caused by inadequate MRO capability. After setting up a certain degree of confidence level, this

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The THY managers can benefit from the model to decide the required number of MRO operations staff and aircraft fleet seat capacity to meet the forecasted demands. Aviation MRO department usually needs skilled and trained staff, so management has to consider the training needs in advance while hiring new MRO staff.

6.2. Future Work

The model has adapted to the Turkish Airlines MRO department and does not reflect all the interactions among the various departments of it due to the limited available data. It may be interesting to expand the model to cover important departments that has impacts on MRO department such as Accounting and Finance, Purchasing, Marketing, Advertising and Human Resource Management. This model can also be regarded as sub-model and can be integrated to various system dynamics model in aviation industry. In both cases, the cause-effect relations and interactions can be observed in a more efficient and wider scope. The model is made generic to adapt to the other airline companies but still it can be tested and improved.

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APPENDIX A. THE MODEL

This appendix presents the system dynamics model and documentation of the developed model in Vensim software.

A type MRO executed aircrafts=
MIN (Potential Aircrafts to Use,potential to end A's)

Units: aircraft

The portion of the planned A type check executed aircrafts with the required man power.

A type MRO generator for week1=
RANDOM UNIFORM(100,100 , 2148)

Units: man*hour/aircraft/Week

It is a random number generator whose range is between 100 and 500 man hour.

A type MRO generator for week2=
RANDOM UNIFORM(100,100 , 7876)

Units: man*hour/aircraft/Week

It is a random number generator whose range is between 100 and 500 man hour.

A type MRO generator for week3=
RANDOM UNIFORM(100,100 , 1974)

Units: man*hour/aircraft/Week

It is a random number generator whose range is between 100 and 500 man hour.

A type MRO generator for week4=
RANDOM UNIFORM(100,100 , 1997)

Units: man*hour/aircraft/Week

It is a random number generator whose range is between 100 and 500 man hour.

actual aircrafts in use=

A type MRO executed aircrafts

Units: aircraft

The number of aircrafts available for use.

aircraft capacity shortfall=

MAX(0,INTEGER(Monthly aircraft shortage filtering ratio* (demand rate-passengers per month

)/(average number of passengers in a flight*average number of flights per aircraft in a month

) - MRO capacity shortfall))

Units: aircraft/Month

The number of additional aircrafts to reach the desired passenger capacity.

"aircraft look-up table":=

GET XLS DATA('MRO_Data_model.xls', 'Yearly', 'a', 'g2')

Units: aircraft/Month

New aircrafts will be incorporated into the fleet according to a plan. This data is hold in this table.

aircraft retirement=

IF THEN ELSE(Time < 2014 ,0,INTEGER (total aircrafts * aircraft retirement rate))

Units: aircraft/Month

The number of aircrafts leaves the system for any reason.

aircraft retirement rate=

0.00833

Units: 1/Month

The percentage of aircrafts leaves the system for any reason.

Aircrafts at C Type MRO= INTEG (

to C type MRO-C type MRO ends,

1)

Units: aircraft

Total number of aircrafts separated for C type MRO.

average number of flights per aircraft in a month=

200

Units: flight/(Month*aircraft)

Average number of flights executed for each aircraft in a month.

average number of passengers in a flight=

139

Units: Passenger/flight

Average number of passenger for each flight.

C type MRO ends=

C type MRO executed aircrafts*C type MRO to Month ratio

Units: aircraft/Month

The number of aircrafts goes into use after the planned C type check.

C type MRO executed aircrafts=

MIN(Aircrafts at C Type MRO,potential to end C's)

Units: aircraft

The portion of the planned C type check executed aircrafts with the required man power.

C type MRO need per month=

INTEGER (total aircrafts * C Type MRO ratio)

Units: aircraft/Month

Auxiliary variable to spot the number of aircrafts that need C type MRO.

C Type MRO ratio=

1/2.5/12

Units: 1/Month

The number of aircrafts need to undergo to C Type MRO checks for each month. Time interval is 2.5 years. (Total aircrafts/2.5 Years/12 Months)

C type MRO to Month ratio=

1

Units: 1/Month

Used for equation unit conversion. All selected aircrafts for C Type MRO should go to MRO facility.

Demand Forecast= INTEG (

demand rate,

1.04e+007)

Units: Passenger

Forecasted passenger demand.

demand rate=

"forecast look-up table"

Units: Passenger/Month

Forecasted monthly demand rate.

flight capacity per month=

INTEGER (actual aircrafts in use*average number of flights per aircraft in a month)

Units: flight/Month

Total number of flights in a month.

"forecast look-up table"= WITH LOOKUP (

Time,

([(2003,0)-(2025,2e+007)],(2003,1.658e+006),(2004,1.742e+006),(2005,1.989e+006),(2006,2.343e+006),(2007,2.66e+006),(2008,2.953e+006),(2009,3.414e+006),(2010,3.717e+006),(2011,4.353e+006),(2012,5.019e+006),(2013,5.909e+006),(2014,6.759e+006),(2015,7.187e+006),(2016,7.849e+006),(2017,8.272e+006),(2018,8.873e+006),(

2019,9.387e+006),(2020,9.981e+006),(2021,1.049e+007),(2022,1.096e+007),(2023
,1.133e+007),(2024,1.2e+007),(2025,1.236e+007)))

Units: Passenger/Month

Forecasted passenger demand look-up table.

hour available per person=

6.5

Units: hour/day

Legal daily maximum potential working hour for an employee (8 Hours-1.5 hours
breaks=6.5 hours)

hourly man power cost=

80

Units: Dollar/man/hour

The cost that includes all the expenses to produce one man*hour
work.

"line maint. oper. staff"=

500

Units: man

The number of MRO staff separated for line maintenance
operations.

"maint. costs"=

man power cost

Units: Dollar/Month

Man power cost for each month.

"Maint. Operations Staff"= INTEG (

staff entering-staff leaving,

2000)

Units: man

Human resource executing the MRO operations

man per aircraft=

35

Units: man/aircraft

Average number of staff needed to meet the MRO requirements of a
single aircraft.

man power cost=

hourly man power cost*used man power

Units: Dollar/Month

Total cost of executed MRO operations for each month.

man power for new aircrafts=

man per aircraft*(purchase of aircrafts + MRO capacity shortfall)+staff leaving

Units: man/Month

The additional resource(man power) need to meet the MRO requirements of all new aircrafts.man per aircraft*MAX(purchase of aircrafts,MRO capacity shortfall)

man power need for A type MRO per aircraft=
weekly A Type MRO checks in a month * (scheduled A type MRO man power per aircraft

+unscheduled A type MRO man power per aircraft)

Units: man* hour/aircraft/Month

Monthly man power need for scheduled and unscheduled A type MRO for each aircraft.

man power need for C type MRO per aircraft=
scheduled C type MRO man power per aircraft+unscheduled C type MRO man power per aircraft

Units: man*hour/(Month*aircraft)

Monthly man power need for scheduled and unscheduled C type MRO for each aircraft.

man power waste rate=
wasted monthly man power*to month

Units: man/Month

Monthly man power waste, in another word, wasted potential resource.

Man Power Wasted= INTEG (
man power waste rate,
0)

Units: man

The potential man power that is not used and wasted. We can also call it spare man power.

Monthly aircraft shortage filtering ratio=
0.5

Units: 1/Month

A filtering parameter to smooth the required additional aircraft size while system was unable to meet the forecasted demand.

monthly staff capacity=
MAX (0,("Maint. Operations Staff"- "line maint. oper. staff")*productivity per person
)

Units: man*hour/Month

Monthly man-power capacity of all MRO departments

MRO capacity shortfall=
MAX(0, IF THEN ELSE(C type MRO need per month + actual aircrafts in use*

to month) > total aircraft MRO desired ratio*total aircrafts*to month
, 0 , INTEGER(to month*(total aircrafts-actual aircrafts in use)
) - C type MRO need per month))

Units: aircraft/Month

It shows the capacity shortfall of MRO facility to meet the MRO requirements of the aircrafts and proposes to increase the MRO capacity considering the related capacity shortfall on resource(man) per aircraft basis.

new aircrafts=

MAX("aircraft look-up table",aircraft capacity shortfall)

Units: aircraft/Month

It is used to retrieve data from the data base (Aircraft look-up data).

Passenger= INTEG (passengers per month,
1.04e+007)

Units: Passenger

Total number of passengers traveled so far.

passengers per month=

flight capacity per month*average number of passengers in a flight

Units: Passenger/Month

The number of passengers traveled in that month.

Potential Aircrafts to Use= INTEG (

C type MRO ends+purchase of aircrafts-aircraft retirement-to C type MRO,
64)

Units: aircraft

The number of aircrafts, except the ones separated for C Type MRO, which needs A type MRO.

potential to end A's=

INTEGER(remaining monthly staff capacity / man power need for A type MRO per aircraft

)

Units: aircraft

It shows the number of A Type checks that can be handled with remaining monthly staff capacity. It also includes the unscheduled A Type checks.

potential to end C's=

INTEGER(monthly staff capacity / man power need for C type MRO per aircraft

)

Units: aircraft

It shows the number of C Type checks that can be handled with

monthly potential man power the at hand. It also includes the unscheduled C Type checks.

productivity per person=
work days in a month*hour available per person*utilization per person
Units: hour/Month
Efficiently used monthly man-power capacity for a single employee

purchase of aircrafts=
new aircrafts
Units: aircraft/Month
Entry of new aircrafts to the system.

remaining monthly staff capacity=
monthly staff capacity-(C type MRO executed aircrafts*man power need for C type MRO per aircraft
)
Units: man*hour/Month
Monthly man-power capacity after execution of C type MRO activities.

scheduled A type MRO man power per aircraft=
A type MRO generator for week1+A type MRO generator for week2+A type MRO generator for week3
+A type MRO generator for week4
Units: man* hour/aircraft/Week
Weekly man power need for scheduled A type MRO for each aircraft. From experience, scheduled A type MRO activities requires 100 to 500 man hour.

scheduled C type MRO man power per aircraft=
5000
Units: man* hour/aircraft/Month
Monthly man power for each aircraft whose C type MRO plan period reached. From experience, scheduled C type MRO activities require 5000 man hour for each 2-3 years.

staff entering=
staff increase
Units: man/Month
Newly employed Maintenance Operations Staff

staff increase=
IF THEN ELSE(Time < 2014, "staff look-up table" , MAX(0,man power for new aircrafts
- man power waste rate*waste man power save filter))
Units: man/Month

Auxiliary variable to balance excess and new human resource need

staff leaving=

IF THEN ELSE(Time < 2014 ,0,INTEGER ("Maint. Operations Staff"* staff leaving
rate per month

))

Units: man/Month

Retiring or leaving staff for any reason

staff leaving rate per month=

0.00416

Units: 1/Month

The percentage of man power leaves the system for any reason.

"staff look-up table":=

GET XLS DATA('MRO_Data_model.xls', 'Yearly', 'a', 'j2')

Units: man/Month

The table that holds the past MRO human resource up to year 2013.

TIME STEP = 0.08333

Units: Month [0,?]

The time step for the simulation.

to C type MRO=

C type MRO need per month

Units: aircraft/Month

The number of aircrafts that need C type MRO.

to month=

1

Units: 1/Month

Variable used in unit conversions.

total aircraft MRO desired ratio=

0.98

Units: Dmnl

The parameter representing the percentage of the aircrafts for
MRO facility to keep the aircrafts airworthy.

total aircrafts=

Aircrafts at C Type MRO+Potential Aircrafts to Use

Units: aircraft

The total size of the aircraft fleet.

Total Flights= INTEG (

total flights per month,

100000)

Units: flight

The total number of flights of the aircraft fleet.

total flights per month=

flight capacity per month

Units: flight/Month

Total number of flights executed for each month.

unscheduled A type MRO man power per aircraft=

$0.6 \times \text{scheduled A type MRO man power per aircraft}$

Units: man* hour/aircraft/Week

Weekly man power need for unscheduled A type MRO for each aircraft. From experience, it almost requires 60% man power of scheduled A type MRO man power.

unscheduled C type MRO man power per aircraft=

$0.6 \times \text{scheduled C type MRO man power per aircraft}$

Units: man* hour/aircraft/Month

Monthly man power need for unscheduled C type MRO for each aircraft. From experience, it almost requires 60% man power of scheduled C type MRO man power.

used man power=

$\text{A type MRO executed aircrafts} \times \text{man power need for A type MRO per aircraft} +$

$\text{C type MRO executed aircrafts} \times \text{man power need for C type MRO per aircraft}$

Units: man*hour/Month

Used man power used MRO operations

utilization per person=

0.6923

Units: Dmnl

It is the average utilization rate of an employee

waste man power save filter=

0.5

Units: Dmnl

Filter to reduce the wasted man power

wasted monthly man power=

$(\text{monthly staff capacity} - \text{used man power}) / \text{productivity per person}$

Units: man

Monthly wasted man power.

weekly A Type MRO checks in a month=

1

Units: Week/Month

The number of weekly A Type MRO Checks have to be executed in a

month.

work days in a month=

24

Units: day/Month

Total number of legal working days in a month.

Table A.1. MRO_Data_model.xls File 'Yearly' Tab Data

	Columns		
Rows	A	G	J
1	Year	Delta Aircrafts	Delta MRO Personnel
2	2000		
3	2001		
4	2002		
5	2003	0	
6	2004	8	250
7	2005	10	250
8	2006	20	500
9	2007	-1	0
10	2008	25	500
11	2009	7	0
12	2010	18	0
13	2011	27	500
14	2012	23	500
15	2013	42	500
16	2014	20	
17	2015	20	
18	2016	20	
19	2017	20	
20	2018	20	
21	2019	20	
22	2020	20	
23	2021	20	
24	2022	20	
25	2023	20	
26	2024	20	
27	2025	20	
28	2026	20	
29		20	
30			
31			

ÖZGEÇMİŞ

Asım TOKGÖZ 08.02.1974 tarihinde Sungurlu’da doğmuştur. Deniz Lisesi’ni 1993 bitirdikten sonra devam ettiği Deniz Harp Okulu’nu 1997 yılında bitirerek Endüstri Mühendisliği dalından mezun olmuştur. 2001-2003 yılları arasında Naval Postgraduate School/ABD’de “Modeling, Virtual Environments and Simulation” dalında Yüksek Lisans programını bitirmiştir. Yine aynı okulda 2010 yılında 1 dönem okuyarak “Command, Control, Comunication, Computer and Intelligence” alanında sertifika almıştır.

1997-2001 yılları Türk Deniz Kuvvetleri harp gemilerinde çeşitli görevlerde çalışmıştır. Yüksek Lisans eğitimini müteakiben ağırlıklı olarak Komuta ve Kontrol sistemleri üzerinde çalışmıştır. 2010 yılında başladığı doktora eğitimine devam etmektedir.

BIOGRAPHY

Asım TOKGÖZ was born on Feb 08, 1974 in Sungurlu. After graduating from Naval High School in 1993, he received his BS degree in Industrial Engineering from the Turkish Naval Academy in 1997 and MS degree from the Modeling, Virtual Environments and Simulation, Naval Postgraduate School, Monterey, CA,USA in 2003. He also joined the same school for one quarter and earned a non-degree certificate in “Command, Control, Communication, Computer and Intelligence”.

He worked in various positions in the Turkish Navy warships between the years 1997-2001. He is currently working toward the PhD degree in Industrial Engineering, Marmara University, Turkey. He is also an engineer and expert at the Turkish Naval Research Center Command. His current research interests include operations research, command and control systems, tactical data links, metaheuristics, system dynamics and applied operations research.