LEBANESE AMERICAN UNIVERSITY

Designing Policies using a MIMO PID Controller for Correlated
Multiple-Policy Multiple-Objective Strategic Planning: A Balanced
Scorecard Approach

By

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To my loving parents

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Joe Khalifeh

ABSTRACT

Strategic planning (SP) is the process of aligning an organization's activities with its own vision and mission. Several strategic planning frameworks and tools were developed such as SWOC, Porter's five forces and PEST analysis. So far the balanced scorecard (BSC), proposed by Norton and Kaplan, is the most consistent since it accounts for strategic measures in four major perspectives. Shaping relevant decision rules to meet the target measures associated with the BSC four perspectives becomes a multiple-policy multi-objective (MPMO) process. During the past four decades, there has been some development of analytical methods that can guide SP analysts in policy makings of large systems. Different policy design techniques are proposed that help in steering organizations towards meeting a target level. Designing policies is usually constructed as a set of single-policy single-objective subsystem where proportional and, at most, derivative feedback control is presented without taking into consideration the four BSC perspectives.

In this thesis we consider a Master's University, such as the Lebanese American University, as the organization. We associate the number of enrolled students, the academic reputation, student-to-faculty ratio and research productivity, and faculty recruitment and faculty development funds with the four BSC perspectives. The policies under consideration are number of faculty to be recruited, development funds to be dedicated to faculty at the associate professorial rank, and development funds to be dedicated to faculty at the professional rank. A 28th-order nonlinear state-space model is constructed in order to reflect the relevant system dynamics. A multiple-input multiple-output (MIMO) Proportional-Integral-Derivative (PID) controller is implemented for shaping the correlated three policies involved in this MPMO system. The associated ten-year target levels are set such that the university reputation is significantly improved, and the overall financial balance is considerably large in order to accommodate for capital expansion. Numerical simulations are included to illustrate the effectiveness of the proposed MPMO systematic approach.

Keywords: Strategic Planning (SP), Balanced Scorecard (BSC), System Dynamics (SD), Multiple-input multiple-output (MIMO), PID Controller.

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Chapter One

Introduction

Strategic planning has helped organizations from corporations to non-profit or governmental institutions align their business activities and decision rules with their strategies and vision. The process relies on identifying the organization's strength and weaknesses and determining how it can explore new opportunities and mitigate risks (Mintzberg, 1978). Conventional strategic planning techniques such as Strengths, Weaknesses, Opportunities and Threats analysis (SWOT), now Strengths, which became Weaknesses, Opportunities and Challenges analysis (SWOC), and Political, Economic, Social and Technological (PEST) analysis do not provide a clear and comprehensive set of measures to take into consideration (Hederson, 1979). Henderson, founder of the Boston Consulting Group (BCG), introduced the concept of "growth-share matrix", which visualizes a company's portfolio in a two-dimensional array of market growth versus relative market share (Hederson, 1979) (Stern, 2006). This framework became popular in the 80's and it laid the foundation of the BCG perspectives (Stern, 2006). The competition over market shares was further discussed by Michael Porter, a pioneer in strategic planning. He emphasized how the five competitive forces determine an industrial market's attractiveness. Porter's five forces refer to the bargaining power of suppliers, bargaining power of customer, threats of new entrants, threats of substitute products and competitive rivalry within an industry (Porter, How Competitive Forces Shape Strategy, 1979) (Porter, Competitive Strategy, 1980). His proposed framework aids to understand the status of the organization in the market and facilitates the shaping of its main competitive strategies. However he fails to provide clear nonfinancial metrics in order to quantify the five forces.

In 1992, David Norton and Robert Kaplan introduced the Balanced Scorecard (BSC) as a way to integrate intangible asset measures into intangible asset management systems. BSC complements financial metrics with metrics from three supplementary perspectives, designated by Customer, Internal Process and Learning and Growth perspectives (Kaplan &

Norton, The balanced scorecards: measures that drive performance, 1992) (Kaplan & Norton, The Balanced Scorecard: Translating Strategy into Action, 1996) (Kaplan & P, Linking the Balanced Scorecard to Strategy, 1996) (Kaplan & P, Having trouble with your strategy? Then map it, 2000) (Kaplan & Norton, Strategy Maps. Converting Intangible Assets into Tangible Outcomes, 2004). The graphical representation of the BSC depicts the four perspectives encircling the organization's vision and strategies and their interactions. These interactions became the basis of measures identification and policy making. BSC borrowed its original concept from a project conducted at General Electric (GE) during the 1950s that aimed to develop performance measures. The outcome of the project supplemented financial metrics with 7 others: market share, productivity, product leadership, public responsibility, personnel development, employee attitudes and balance between short-range and long-range objectives (Lewis, 1955). The BSC customer perspective is represented by the market share. The internal process perspective includes the productivity, product leadership and public responsibility. The learning and growth perspective encompasses personnel development and employee attitudes. The balance between short and long-range goals represents the main purpose of using BSC (Kaplan, Conceptual Foundations of the Balanced Scorecard, 2010). The framework proposed by Norton and Kaplan gained a lot of popularity for its proven powerful insights about performance measures and became widely used in various industries as a platform for strategic planning (Kaplan, Conceptual Foundations of the Balanced Scorecard, 2010). The main advantages of the BSC are that it relies on few performance measures compared to the complexity of the organization or system, and on the integration of measures from different fields other than the financial perspective. Akkermans and van Oorschot discuss in their work in 2002 the five shortcomings of using the BSC in strategic planning (Akkermans & van Oorschot, 2002). They claim that the causal interaction between perspectives and measures do not capture the actual dynamics of the system. They next discuss the failure of the BSC model to account for time-delays between cause and effect links, which are present in a real system. These delays alter the dynamics of cause and effect loops and cannot be seen unless causes and effects are separated in time. Also, they criticize the BSC for the lack of measure relevance validation mechanism. Reducing the list of measures to a manageable size may become a

disadvantage if the measures were poorly selected. They move on to claim that the interaction between strategy and operations is insufficient and that there exists a lack of integration between the strategic scorecard and the operational level measures. Finally, they argue that the BSC is internally focused and does not account for market competition (Akkermans & van Oorschot, 2002). In order to overcome these limitations, Akkermans and van Oorschot, and others, coupled the BSC with a system dynamics model (Akkermans & van Oorschot, 2002) (Akkermans & Oorschot, 2005) (Bianchi & Montemaggiore, 2008). This helped identify key measures and their correlated dynamic behavior; however they failed to provide a design rule control strategy.

Such strategies have existed in the literature of system dynamics since its early usage. System dynamics was put forth by Professor Jay W. Forrester at the MIT Sloan School of Management as a mean to understand and model complex industrial organizations. It provided the system analyst with powerful simulation tools for visualizing the complex dynamics behavior of such systems (Forrester, Industrial Dynamics, 1961). The method relied on constructing causal links between different rates and levels, reducing the understanding complexity of the model to a set of first order differential equations. The potential of this method attracted several system analysts and scaled the use of system dynamic modeling from industrial company level to urban design, and to worldwide systems (Forrester, Industrial Dynamics, 1961) (Forrester, Urban Dynamics, 1961) (Forrester, World Dynamics, 1979). It quickly became an important tool for strategic policy design (Warren, 2008) (Morecroft, 2007). Systems dynamics models are usually approached as control problems (Mohapatra K. J., Structural equivalence between control systems theory and system dynamics, 1980) (Mohapatra & Shushil, 1985) (Sharp, Optimal Control Theory as a Framework for the Interpretation of System Dynamics, 1978). Simulations help the system analyst understand the system and visualize its outputs for certain decision rules. These rules are then adjusted to eliminate the discrepancies between a certain desired objective and the current state of the system (Dyson & Foster, 1983) (Tomlinson & Dyson, 1983). This tedious and almost impossible process was replaced by automated control strategies that rely on proportional or, at most, derivative feedback control (Forrester, Industrial Dynamics, 1961) (Forrester, Urban Dynamics, 1961) (Forrester, World Dynamics,

1979) (Warren, 2008) (Morecroft, 2007) (Sterman, 2000). Sharp and Henry (1979) proposed a way to design policies using a PID controller, based on the Ziegler Nichols method (Sharp & Henry, Designing Policies the Ziegler Nichols Way, 1979). Sharp and Henry however considered a single-input single-output linear system in their paper. Sharp considered nonlinear systems earlier in his work on system dynamics and proposed in 1976 with Ratnatunga a way to linearize systems and reduce their order (Ratnatunga & Sharp, 1976) (Mohapatra K. J., Nonlinearity in system dynamics models, 1980). The purpose of their work was to simplify systems in order to reduce computational time. They also relied on initial simulation results in order to identify redundant variables that can be neglected in order reduction. At that point, design rules were applied independently on individual policies, overlooking the interdependencies within the system.

Kampmann (1996) proposed a way to identify loop strength and influence on the dynamic behavior of the system using loop eigenvalue elasticity analysis (LEEA) (Kampmann, Feedback loop gains and system behavior, 1996). This method was first used as eigenvalue elasticity analysis (EEA) in the doctoral dissertation of N Forrester back in 1982. Forrester's work did not receive much attention at first until Kampmann presented his own. EEA consists of decomposing the system into characteristic behavior mode, each characterized by an eigenvalue of the linearized matrix. Then it examines the effect of each small change in system parameter on each eigenvalue (Kampmann, Feedback loop gains and system behavior, 1996). This method became a formal tool to identify important structures in the model as they affect certain modes of behavior. Kampmann and Olivia later on presented three case studies using LEEA with promising results (Kampmann & Olivia, Loop eigenvalue elasticity analysis: three case studies, 2006) (Kampmann & Olivia, Structural dominance analysis and theory building in system dynamics, 2008).

Most recently, (Tsan, Charlle, & Loo, 2012) made use of LEEA to propose a robust optimization model-based approach to parametric design of system dynamics models. In their work, they show how LEEA helps determine the target settings of the optimization process. Their results were quite significant in presence of high parameter uncertainties.

In this thesis, we propose a new way of designing policies for a correlated multiple-policy multiple-objective (MPMO) system using a PID controller. The Lebanese American University (LAU) is the organization of interest. We draw the input-output structure of the system from the four perspectives of the BSC model. We then derive its dynamic structure through system dynamics modelling. The model is then mapped into state-space, and linearized. Numerical simulations of the controlled system demonstrate a significant performance and robustness of the proposed controller.

In chapter 2 we look at relevant background information concerning BSC, system dynamics (SD) and state-models. A small example is considered in order to illustrate the methods used. In chapter 3 we model LAU starting with the BSC approach, and then couple it with an SD model. Chapter 4 presents parameter assignments and numerical simulation to validate our SD model. In chapter 5, we map the system into state-space, define its outputs, linearize it and apply control. The simulation results of the controlled system are shown at the end of chapter 5. Chapter 6 concludes the work and presents our future work.

Chapter Two

Background Information on BSC, SD and State-Space

This chapter provides background information about several concepts explored in this thesis. We will first briefly explain the Balanced Scorecard strategic planning system, and then we will present the basics of System Dynamics. Next, we will propose a way to go from a System Dynamics model to a state-space model. Finally, we will concisely discuss a linearization method.

Let us first introduce the Balanced Scorecard.

2.1 BSC

The main advantage of the BSC technique is that it provides measures other than the financial metrics that help capture the performance of the organization. These measures are categorized into four perspectives:

- 1) Financial
- 2) Customer
- 3) Internal Business Process
- 4) Learning and Growth

Kaplan and Norton provide the following diagram that encompasses all four perspectives and their interactions.

Figure 2.1 BSC Perspectives [12]

The objectives of each perspective are mainly set by the Vision and Strategy of the company. Based on these objectives, relevant measures are defined. An example of Customer measure could be the market share or the product adoption rate. Another measure could be the customer satisfaction, which can be measured by surveying the customer. Typical Internal Business Process measures could be the productivity or efficiency. Learning and Growth measures are usually related to personnel development, attitudes of employees and their capacities.

Once these measures are identified, the next step would be to set realizable targets and devise initiatives to reach them.

The scorecard is evaluated every period of time and the measures are compared to the targets. Whenever discrepancies arise, necessary initiatives are taken into consideration in order to steer back the organization towards its targets. This strategic planning system ensures that the organization will align its activities with its vision and strategy.

Using the four-perspective approach of the BSC is what we will borrow from the Balanced Scorecard in this thesis. Discussing it further becomes outside of the scope of this work.

In what follows, we introduce the basic concept of System Dynamics and to go from a stock-and-flow diagram to state-space representation.

2.2 System Dynamics

The ease of understanding and using system dynamics makes it a very powerful and popular modeling technique. Its technical complexity is limited to first order differential equations. The real challenge is to thoroughly understand the system and identify all the relevant cause and effect relationships. It is therefore the task of skilled and experienced system dynamicists to model the system at hand. Most of the time, they refer to experts in the field related to the organization or to the ecosystem they are trying to analyze. In other words, modeling the system is very cumbersome and difficult, and requires a lot of knowledge about the system itself. Elaborating on this part of systems modeling is beyond the extent of this thesis. In what follows, we will summarize the main system dynamics tools that helped us shape the model of the university system at hand.

2.2.1 Causal Loop Diagrams

A causal loop diagram is a graphical representation of cause and effect relationships and feedback loops. A causal loop diagram representing drug-related crime is pictured in figure 2.2.

This graph includes all the constituents of a causal loop diagram. It can be clearly seen that a causal relationship is represented by an arrow. A “+” or “-” sign is added on the pointing end of the arrow to indicate if an increase in the previous variable results in an increase (+) or decrease (-) in the other variable. This system has one feedback loop, which is identified as “Crime Spiral”. The “R” (for reinforcing) explains the loop sign and direction.

Figure 2.2 Drug Related Crime Causal Loop Diagram [20]

Let us now interpret the system. Consider that drug-related crime has increased. This would call for more police action, which will result in more drug seizures, therefore less drug supply. Drug addicts always demand drugs, and since there is less supply, the price of drugs will increase. In order to afford drugs at a higher price, addicts will commit more crimes. This will go on and on. This feedback loop is defined as a reinforcing loop, since a change at the beginning of the loop resulted in a change in the same direction. Hence the letter R in the middle of the loop. If the initial change resulted in a change in the opposite direction, the loop would become a balancing loop, labeled B.

This example shows that causal loop diagrams are abstract in nature and are used to understand the system from a generic point of view. Although they do not accurately describe the system, they are a good starting point in the modeling process and most importantly help us identify major feedback loops in the system.

2.2.2 Stock and Flow Diagrams

Stock and flow diagrams are used to capture the dynamics of the system. Take for example the model in figure 2.3. The stock at hand has certain input and output flow rates. The actual value of the stock is the accumulation of the difference between the inflow and outflow over time.

Figure 2.3 Simple Stock and Flow Diagram

It can therefore be summarized by the following differential equation:

$$\frac{d(\text{Stock Accumulation})_{(t)}}{dt} = \text{Inflow}_{(t)} - \text{Outflow}_{(t)}$$

Applying the definition of the derivative we can rewrite the above equation as:

$$\frac{\text{Stock Accumulation}_{(t+dt)} - \text{Stock Accumulation}_{(t)}}{dt} = \text{Inflow}_{(t)} - \text{Outflow}_{(t)}$$

$$\text{Stock Accumulation}_{(t+dt)} - \text{Stock Accumulation}_{(t)} = (\text{Inflow}_{(t)} - \text{Outflow}_{(t)}) \times dt$$

$$\text{Stock Accumulation}_{(t+dt)} = \text{Stock Accumulation}_{(t)} + (\text{Inflow}_{(t)} - \text{Outflow}_{(t)}) \times dt$$

For a sufficiently small Δt , we can write:

$$\text{Stock Accumulation}_{(t+\Delta t)} \approx \text{Stock Accumulation}_{(t)} + (\text{Inflow}_{(t)} - \text{Outflow}_{(t)}) \times \Delta t$$

This formula shows that the Stock Accumulation in the next time step is equal the sum of the Stock Accumulation in the current time step and the difference of the Inflow and Outflow during this time step.

If we set $t = k\Delta t$ and $f(k\Delta t) \stackrel{\text{def}}{=} f[k]$, we can rewrite the now discretized equation as:

$$\begin{aligned} \text{Stock Accumulation}_{[k+1]} = & \text{Stock Accumulation}_{[k]} + (\text{Inflow}_{[k]} - \\ & \text{Outflow}_{[k]}) \times \Delta k \end{aligned} \tag{2.1}$$

For simplicity, we will replace the brackets [] by parenthesis () for the rest of the thesis.

A stock and flow diagram is constructed by defining all the relevant stocks and their interactions. Figure 2.4 depicts a simple systems dynamics model.

Figure 2.4 Simple System Dynamics Model

The Workers and Production are the only two stocks in the model. The arrows indicate causal links. Let us briefly analyze the dynamics of this system. The number of workers available in the plant/company/industry will dictate the production rate. Consider the Worker's Capacity to be 5 products per worker per month, this means that 100 workers will produce 500 products per month, which is the production rate. The number of workers depends on the hiring rate and the departure rate. The hiring rate is set by the company and can be changed freely. The departure rate is calculated based on previous statistics. Consider that studies conducted on the company showed that 3% of the workers leave the company every month. This is known as the layoff rate. The Departure Rate becomes therefore the product of the actual number of workers and the Layoff Rate. Hence the causal link between Workers and Departure Rate. A similar relationship exists between Production, Time to move product and Supply. Assume the company can mobilize products once per 2 months, this means that the Supply in one month is half the Production available at this month.

Once the modeling process is done, we can formulate the equations describing the system. The model has two stocks, Workers and Production, and their equations were formulated above in equation (2.1).

Now let us look at the causal links depicted in the diagram in figure 2.4. The variables Departure Rate, Production Rate, Supply and Supply/Demand Gap have certain inputs. These inputs are

indicated by the arrows flowing into these variables. Each variable is therefore a function of the inputs at that node. This function can be of any type, and produces an output at this node. This output could serve as an input for another node.

The remaining variables Hiring Rate, Worker's Capacity, Time to move product, Layoff Rate and Demand can be categorized as either system parameters, or system inputs or policies. The Worker's Capacity, for example, is a constant that can be measured statistically. It is therefore a system parameter and can be time variant. The same applies for the Layoff Rate, Time to move product and the Demand.

The Hiring Rate on the other hand depends on the company's policy and can be therefore changed by the company. Consequently, it is considered as an input to the entire system.

Referring to what was mentioned above, we can write the following:

$$\begin{aligned}
 \mathbf{Workers}_{(k+1)(workers)} &= \mathbf{Workers}_{(k)(workers)} \\
 &+ \left(\mathbf{Hiring Rate}_{(k)\left(\frac{workers}{month}\right)} \right. \\
 &\left. - \mathbf{Departure Rate}_{(k)\left(\frac{workers}{month}\right)} \right) \times \Delta k_{(months)}
 \end{aligned} \tag{2.2}$$

$$\begin{aligned}
 \mathbf{Departure Rate}_{(k)\left(\frac{workers}{month}\right)} &= \mathbf{Workers}_{(k)(workers)} \times \mathbf{Layoff Rate}_{\left(\frac{workers}{worker \times month}\right)}
 \end{aligned} \tag{2.3}$$

$$\begin{aligned}
 \mathbf{Production Rate}_{(k)\left(\frac{products}{month}\right)} &= \mathbf{Workers}_{(k)(workers)} \\
 &\times \mathbf{Worker's Capacity}_{\left(\frac{products}{worker \times month}\right)}
 \end{aligned} \tag{2.4}$$

$$\begin{aligned}
\mathbf{Production}_{(k+1)(products)} &= \mathbf{Production}_{(k)(products)} \\
&+ \left(\mathbf{Production\ Rate}_{(k)\left(\frac{products}{month}\right)} - \mathbf{Supply}_{(k)\left(\frac{products}{month}\right)} \right) \\
&\times \Delta k_{(months)}
\end{aligned} \tag{2.5}$$

$$\begin{aligned}
\mathbf{Supply}_{(k)\left(\frac{products}{month}\right)} &= \mathbf{Production}_{(k)(products)} \\
&\times \mathbf{Time\ to\ move\ product}_{(month^{-1})}
\end{aligned} \tag{2.6}$$

$$\begin{aligned}
\mathbf{Supply/Demand\ Gap}_{(k)\left(\frac{products}{month}\right)} &= \mathbf{Supply}_{\left(\frac{products}{month}\right)} - \mathbf{Demand}_{\left(\frac{products}{month}\right)}
\end{aligned} \tag{2.7}$$

Looking at the diagram and the equations formulated above, we can see that the variable names are illustrative enough to understand the stock and flow diagram directly. This is very common in system dynamics modeling since it helps keep track of all variables in the system. Another observation can be made related to the units assigned to variables. It can be seen that all units are consistent across. A dimensional analysis can therefore double check the correctness of the equations.

Now that all the equations are formulated and all parameters and inputs identified, we can proceed with simulating the system.

2.2.3 Simulation

One last step before simulating is to assign values to parameters and inputs, and set the initial condition for the stocks. For this example, we will consider the following:

$$\mathbf{Workers}_{(0)} = \mathbf{100}_{(workers)}$$

$$\mathbf{Production}_{(0)} = \mathbf{500}_{(products)}$$

$$\mathbf{Worker's\ Capacity} = \mathbf{5}_{(\frac{products}{worker \times month})}$$

Layoff Rate

$$= \mathbf{0.05}_{(\frac{workers}{worker \times month})}$$

Time to move product

$$= \mathbf{0.5}_{(month^{-1})}$$

$$\mathbf{Demand} = \mathbf{1000}_{(\frac{products}{month})}$$

Let us assume it is the company's policy to hire 4 new workers every month:

$$\mathbf{Hiring\ Rate} = \mathbf{4}_{(\frac{workers}{month})}$$

Figures 2.5, 2.6 and 2.7 show the result of the simulation over 100 months. The number of workers decreases from the initial 100 to approximately 80. It will actually stop varying once it reaches 80 since the Hiring Rate (4 workers/month) becomes equal to Departure Rate ($80 \times 0.05 = 4$ workers/month). The production increases to about 950 and then decreases to stabilize around 800. This is the result of the stabilization of the number of workers around 80.

The Production Rate will then be $80 \times 5 = 400$ products/month. The Supply is half the Production, which is also equal to 400 for a Production of 800. This explains why the Production also stabilizes after a certain amount of time. Since the Demand is assumed constant over the analysis period, the Supply/Demand Gap behaves exactly like the Supply however in the opposite direction (if $\text{supply} < \text{demand}$, the gap is positive).

Figure 2.5 Simple Example: Workers

Figure 2.6 Simple Example: Production

Figure 2.7 Simple Example: Supply and Demand

The power of simulation lies not only in visualizing what is happening, but also in finding a scenario that will yield to a certain desired goal. This goal is usually reflected in one or more variables in the system and these variables are considered to be outputs of the system. Once strategic goals are defined, the simulation process will help in steering the system towards them. The task of an analyst becomes to evaluate the output for a certain scenario, and based on the simulation results, change the input in order to meet the desired output. This is known as a typical control problem. The diagram in figure 2.8 shows how the problem is formulated. Once the Desired Outputs are set, the Analyst makes the necessary Adjustments to eliminate the Discrepancies between the Desired and Actual Output. Note that the adjustments are made on the input variables, or policies, and not on the system parameters. This process is repeated over and over again until the Discrepancies are reduced to an arbitrary value.

Figure 2.8 Control Problem Diagram

Consider in our case we want to reduce the Supply/Demand Gap to 200 products/month within 50 months. In the initial scenario, a Hiring Rate of 4 workers/month yielded a much bigger gap even at 100 months. Let us double this rate. Figure 2.9 shows the Supply and Demand results. We can clearly see that doubling the rate did not yield the desired output in 50 months, however it reduced the gap. We should therefore try a slightly higher rate.

Figure 2.9 Supply and Demand for a Hiring Rate of 8

For a rate of 9 workers/month, we reach a gap of 200 products/month way before 50 months (around 30 months), as shown in figure 2.10. This could be considered as a good solution. Therefore the company's policy would be to hire an average of 9 new workers/month.

Assume we wish to find the critical Hiring Rate, that is the rate for which the gap becomes 200 after 50 months. Since 9 workers/month acted faster than 50 months, the Hiring Rate should be decreased. After a few iterations of trial and error, the critical rate was found to be 8.3 new workers/month. The output is shown in figure 2.11. The desired output is met in the desired time; however coming up with such policies was very cumbersome, since it relies on trial and error. For a more complex system, such as the one proposed later in the thesis, it could be impossible to come up with such scenarios. This is because shaping the policies, or input values, relies on human intuition, which could filter out feasible or even optimal solutions. No matter how well we understand systems, due to their complexity, they may exhibit counter-intuitive behaviors. This makes the human analyst a poor decision making agent.

That is why we propose in chapter 5, a new decision making process: a PID controller.

Figure 2.10 Supply and Demand for a Hiring Rate of 9

Figure 2.11 Supply and Demand for a Hiring Rate of 8.3

2.3 System Dynamics to State-Space

Control problems are usually formulated in state-space. Therefore before proceeding to controller design, it is convenient to map the problem into state-space equations. State-space equations are of the form:

$$\dot{x}(t) = f(x(t), u(t)) \quad (2.8)$$

$$y(t) = h(x(t), u(t)) \quad (2.9)$$

Where $x(t) = (x_1(t), x_2(t), \dots, x_n(t))^T$ is the set of state variables,

$u(t) = (u_1(t), u_2(t), \dots, u_m(t))^T$ is the set of input variables,

$f(t) = (f_1(x(t), u(t)), f_2(x(t), u(t)), \dots, f_n(x(t), u(t)))$ is the set of state equations,

$y(t) = (y_1(t), y_2(t), \dots, y_p(t))^T$ is the set of outputs and

$h(t) = (h_1(x(t), u(t)), h_2(x(t), u(t)), \dots, h_p(x(t), u(t)))$ is the set of output coupling

functions. The discretized problem is of the form:

$$X(k + 1) = F(X(k), U(k)) \quad (2.10)$$

$$Y(k) = H(X(k), U(k)) \quad (2.11)$$

2.3.1 From System Dynamics to State-Space

In order to be able to write the state-space equations, the state variables must first be identified. Equation (2.10) implies that the values of the state variables in the next time step are a function of the values of the state variable in the current time step. This dynamic behavior is similar to the one of the stocks defined earlier in Equation (2.1). We can therefore write:

$$\begin{aligned}x_1 &= \textit{Workers} \\x_2 &= \textit{Production}\end{aligned}$$

In order to simplify the equations, we will define the following:

$$\begin{aligned}c_W &= \textit{Worker's Capacity} \\r_L &= \textit{Layoff Rate} \\r_D &= \textit{Departure rate} \\r_P &= \textit{Production Rate} \\t_P &= \textit{Time to move product} \\s &= \textit{Supply} \\d &= \textit{Demand} \\g &= \textit{Supply/Demand Gap}\end{aligned}$$

Since the Hiring Rate was considered as the system input, and the Supply/Demand Gap as the system output, we can define:

$$\begin{aligned}u &= \textit{Hiring Rate} \\y &= \textit{Supply/Demand Gap}\end{aligned}$$

We can therefore rewrite equations (2.2), (2.5) and (2.7) as follows:

$$x_1(k+1) = x_1(k) + u(k) - r_D(k) \quad (2.12)$$

$$x_2(k+1) = x_2(k) + r_P(k) - s(k) \quad (2.13)$$

$$y(k) = d - s(k) \quad (2.14)$$

From equation (2.4), (2.5) and (2.6), we get:

$$r_D(k) = x_1(k) \times r_L \quad (2.15)$$

$$r_P(k) = x_1(k) \times c_W \quad (2.16)$$

$$s(k) = x_2(k) \times t_P \quad (2.17)$$

Replacing (2.15), (2.16), (2.17) in (2.12), (13), (14), we get:

$$\begin{aligned} x_1(k+1) &= x_1(k) \times (1 - r_L) + u(k) \\ &= f_1(x_1(k), x_2(k), u(k)) \end{aligned} \quad (2.18)$$

$$\begin{aligned} x_2(k+1) &= x_1(k) \times c_W + x_2(k)(1 - t_P) \\ &= f_2(x_1(k), x_2(k), u(k)) \end{aligned} \quad (2.19)$$

$$y(k) = d - x_2(k) \times t_P = h(x_1(k), x_2(k), u(k)) \quad (2.20)$$

Let $X(k) = (x_1(k), x_2(k))^T$ and $F(X(k), u(k)) = (f_1(X(k), u(k)), f_2(X(k), u(k)))$, we can write the last three equations as:

$$X(k+1) = F(X(k), u(k)) \quad (2.21)$$

$$y(k) = h(X(k), u(k)) \quad (2.22)$$

Equations (2.21) and (2.22) are nothing but the state space equations defined in (2.10) and (2.11). Figures 2.12, 2.13 and 2.14 show the state space simulation results for an input of 4 (Hiring Rate). Simulations were done on MATLAB. It is clear that the results match perfectly the one in the original simulation in system dynamics shown in figures 2.5, 2.6 and 2.7.

Figure 2.12 Simulation in State Space: Workers

Figure 2.13 Simulation in State-Space: Production

Figure 2.14 Simulation in State-Space: Supply and Demand

Let $Y(k) = y(k) - d$, we can therefore write equations (2.18), (2.19) and (2.20) as:

$$\begin{pmatrix} x_1(k+1) \\ x_2(k+1) \end{pmatrix} = \begin{pmatrix} 1-r_L & 0 \\ c_W & 1-t_P \end{pmatrix} \begin{pmatrix} x_1(k) \\ x_2(k) \end{pmatrix} + \begin{pmatrix} 1 \\ 0 \end{pmatrix} u(k) \quad (2.23)$$

$$Y(k) = (0 \quad -t_P) \begin{pmatrix} x_1(k) \\ x_2(k) \end{pmatrix} \quad (2.24)$$

Which is of the form:

$$X(k+1) = AX(k) + Bu(k) \quad (2.25)$$

$$Y(k) = CX(k) + Du(k) \quad (2.26)$$

Where $A = \begin{pmatrix} 1-r_L & 0 \\ c_W & 1-t_P \end{pmatrix}$ is the state matrix, $B = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ is the input matrix, $C = (0 \quad -t_P)$ is the output matrix and $D = 0$ is the feed-forward matrix. This system is a linear system, since all state variables and outputs can be expressed as a linear combination of the state variables and inputs. Also, since the parameters r_L, c_W, t_P and d were chosen to be constants, the above system becomes time invariant. That is, matrices A, B, C and D will not change values over time. Otherwise, the system becomes a Linear Time Variant and is represented in equations (26) and (27).

$$X(k+1) = A(k)X(k) + B(k)u(k) \quad (2.27)$$

$$Y(k) = C(k)X(k) + D(k)u(k) \quad (2.28)$$

Most systems are not linear as the one above. Real life systems contain a great amount of non-linearity, just like the one considered in chapter 3. Such systems cannot be formulated as in equations (2.25) and (2.26) or (2.27) and (2.28). However the controller design relies greatly on the knowledge of A, B, C and D. For non-linear systems, these matrices do not exist, but can be approximated by linearizing the model.

2.3.2 Linearization

As mentioned above, knowledge of the state, input and output matrices is crucial in controller design. They can be estimated by linearizing the model.

Consider the system given in equations (2.10) and (2.11) with n state variables, m input variables and q output variables. Applying Taylor series expansion around operating point X_o and U_o , we get:

$$\begin{aligned}
 X(k+1) = & F(X_o(k), U_o(k)) + \left. \frac{\partial F}{\partial X} \right|_{X_o(k), U_o(k)} (X(k) - X_o(k)) \\
 & + \left. \frac{\partial F}{\partial U} \right|_{X_o(k), U_o(k)} (U(k) - U_o(k)) \\
 & + \frac{1}{2!} \left. \frac{\partial^2 F}{\partial X^2} \right|_{X_o(k), U_o(k)} (X(k) - X_o(k))^2 \\
 & + \frac{1}{2!} \left. \frac{\partial^2 F}{\partial U^2} \right|_{X_o(k), U_o(k)} (U(k) - U_o(k))^2 \\
 & + \text{higher order terms}
 \end{aligned} \tag{2.29}$$

Let us neglect the quadratic and higher order terms for small variations of $(X(k) - X_o(k))$ and $(U(k) - U_o(k))$. We get:

$$\begin{aligned}
X(k+1) = F(X_o(k), U_o(k)) &+ \left. \frac{\partial F}{\partial X} \right|_{X_o(k), U_o(k)} (X(k) - X_o(k)) \\
&+ \left. \frac{\partial F}{\partial U} \right|_{X_o(k), U_o(k)} (U(k) - U_o(k))
\end{aligned} \tag{2.30}$$

Where $F(X_o(k), U_o(k)) = X_o(k+1)$, $\left. \frac{\partial F}{\partial X} \right|_{X_o(k), U_o(k)} = \left(\begin{array}{cccc} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \dots & \frac{\partial f_1}{\partial x_n} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & & \frac{\partial f_2}{\partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial x_1} & \frac{\partial f_n}{\partial x_2} & \dots & \frac{\partial f_n}{\partial x_n} \end{array} \right) \bigg|_{X_o(k), U_o(k)}$ is the

Jacobian of F with respect to X evaluated at operating points $X_o(k)$ and $U_o(k)$, $\left. \frac{\partial F}{\partial U} \right|_{X_o(k), U_o(k)} =$

$\left(\begin{array}{cccc} \frac{\partial f_1}{\partial u_1} & \frac{\partial f_1}{\partial u_2} & \dots & \frac{\partial f_1}{\partial u_m} \\ \frac{\partial f_2}{\partial u_1} & \frac{\partial f_2}{\partial u_2} & & \frac{\partial f_2}{\partial u_m} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial f_n}{\partial u_1} & \frac{\partial f_n}{\partial u_2} & \dots & \frac{\partial f_n}{\partial u_m} \end{array} \right) \bigg|_{X_o(k), U_o(k)}$ is the Jacobian of F with respect to U evaluated at operating

points $X_o(k)$ and $U_o(k)$.

Let $\bar{X}(k) = X(k) - X_o(k)$ and $\bar{U}(k) = U(k) - U_o(k)$, the system in equation (30) can be written as:

$$\bar{X}(k+1) = A(k)\bar{X}(k) + B(k)\bar{U}(k) \tag{2.31}$$

Where $A(k) = A(X_o(k), U_o(k)) = \left. \frac{\partial F}{\partial X} \right|_{X_o(k), U_o(k)}$ and $B(k) = B(X_o(k), U_o(k)) = \left. \frac{\partial F}{\partial U} \right|_{X_o(k), U_o(k)}$.

This model is the same as the linear time-variant model defined in equation (26).

The same concept applies to the output variables and we end up with the following equation:

$$\bar{Y}(k) = C(k)\bar{X}(k) + D(k)\bar{U}(k) \tag{2.32}$$

Where $\bar{Y}(k) = Y(k) - Y_o(k)$,

$$C(k) = C(X_o(k), U_o(k)) = \frac{\partial H}{\partial X} \bigg|_{X_o(k), U_o(k)} = \begin{pmatrix} \frac{\partial h_1}{\partial x_1} & \frac{\partial h_1}{\partial x_2} & \dots & \frac{\partial h_1}{\partial x_n} \\ \frac{\partial h_2}{\partial x_1} & \frac{\partial h_2}{\partial x_2} & \dots & \frac{\partial h_2}{\partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial h_q}{\partial x_1} & \frac{\partial h_q}{\partial x_2} & \dots & \frac{\partial h_q}{\partial x_n} \end{pmatrix} \bigg|_{X_o(k), U_o(k)}, \text{ and}$$

$$D(k) = D(X_o(k), U_o(k)) = \frac{\partial H}{\partial U} \bigg|_{X_o(k), U_o(k)} = \begin{pmatrix} \frac{\partial h_1}{\partial u_1} & \frac{\partial h_1}{\partial u_2} & \dots & \frac{\partial h_1}{\partial u_m} \\ \frac{\partial h_2}{\partial u_1} & \frac{\partial h_2}{\partial u_2} & \dots & \frac{\partial h_2}{\partial u_m} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial h_q}{\partial u_1} & \frac{\partial h_q}{\partial u_2} & \dots & \frac{\partial h_q}{\partial u_m} \end{pmatrix} \bigg|_{X_o(k), U_o(k)}.$$

2.4 Conclusion

In this chapter we saw how a balanced scorecard is built. The key is to identify all the relevant measures and classify them into four perspectives: Financial, Customer, Internal Business Process and Learning and Growth. Next we discussed the basics of System Dynamics and the different steps to build a stock-and-flow diagram. A simple example was proposed for which we modeled the stock-and-flow diagram and formulated the dynamic equations. We identified the system inputs, parameters and outputs. Based on the simulations, we were able to shape policies, or find a certain input, that would steer the system towards a certain desired output. This process was found to be cumbersome and relied greatly on trial and error. Next we proposed a way to convert a system dynamics model into a state-space model, which is necessary for the controller design. This can be done by setting the stocks in the system as state variables and write the dynamic equations at the stocks as state equations. The simulation of the state-space model was exactly similar to the simulation of the system dynamics model, which validates our proposed conversion technique.

In what follows, we will model the non-linear system at hand, a master's university such as LAU, starting by determining the four BSC perspectives, which will be the basis of the system dynamics model.

Chapter Three

Modeling a Master's University

In order to model such a complex system, we need to identify all relevant perspectives and their interactions. As mentioned earlier, the Balanced Score Card technique (BSC) provides a good strategy-oriented framework to identify these perspectives. The process relies on categorizing key components and mapping them into four perspectives: 1) Financial, 2) Customer, 3) Internal Processes, and 4) Learning and Growth. In what follows, we determine what constitutes the different perspectives pertaining to LAU.

3.1 Balanced Score Card Model

Even though LAU is a non-profit organization, its financial success is crucial for the university's sustainability and growth.

3.1.1 Financial Perspective

This success can be characterized by increasing the revenues and/or lowering the costs.

However LAU, as many universities in Lebanon, draws 80% of its revenues from the tuitions of students.

Therefore financial success is satisfied by attracting more students and/or increasing the tuition fees. Let us assume that the university wishes to keep its fees constant over the analysis period.

3.1.2 Customer Perspective

Students' attraction to universities and their satisfaction depends on several factors such as services, accreditation, programs offered, campus life, geographical location, diversity... but most importantly on local and the worldwide scholarly reputation of the university. In this thesis, we will only consider the contribution of the latter in attracting new customers, or students.

3.1.3 Internal Process Perspective

A university's reputation is directly affected by the performance and quantity of its faculty members. One looks mainly into the quality of teaching and the amount of research and publications to determine the scholarly performance of any university. However, teaching quality depends on several factors, some too difficult to measure and quantify. Other subsidiary quantifiable measures are considered; namely faculty research impact and student-to-faculty ratio (SFR). The lower the ratio, the more time the faculty members can dedicate to each student. Research impact is considered by most university ranking agencies, whereas Times Higher Education and QS include the SFR in their methodologies.

The productivity in research can be estimated by the quality and quantity of publications and citations. This measure reflects the scholarly performance of faculty.

As far as the faculty members are concerned, it is also important to talk about different professor ranks and promotion policies. There are typically three ranks of faculty: Assistant, Associate and Full professors, listed in ascending order of seniority. The administrative responsibilities of professors differ from rank to rank. Assistant professors usually are not assigned significant extra-curricular tasks. In most cases, they are, to the most, appointed to serve on a certain administrative committee. Furthermore, they are motivated to perform their best in order to secure a tenured position. They are therefore expected to be the most productive in terms of research.

To ensure a tenured position, they must be promoted to Associate Professors. This process is described by the university's promotion policy, which is largely based on research productivity. Discussing these policies is considered beyond the scope of this thesis.

Once Promoted to Associate Professor, the administrative tasks become harder, in nature and in number. Tenured faculty normally become more involved in services and possibly administration and less research oriented.

Another important factor responsible for this drop in research productivity or academic development is the lack of motivation among tenured faculty, as well as the age factor.

It is also essential that we mention the efficiency of the non-academic staff, which contributes a lot to the institution's well-being. But again as mentioned earlier, the key indicators for the university scholarly reputation are reduced to the quality of teaching, or SFR, and the research productivity. Both measures are directly related to the reputation of the university.

3.1.4 Learning and Growth Perspective

It is crucial to know how to manage organizational resources in order to meet strategic goals. This is realizable by strategically shaping policies that most importantly account for learning and growth. In relevance to our system, these policies would mainly tackle teaching quality, promotions and research productivity issues. Teaching quality can be maintained or even improved by hiring more faculty members.

As for research productivity, we mentioned earlier that Associate and Full professors are less productive in research than Assistant Professors. To motivate them again, the department, for example, reduces their teaching load. This is done through course release. Sometimes the university would secure grants or funds to help professors in their research. Another way of motivating the faculty members would be promotions. In all cases, financial resources are needed.

Figure 3.1 depicts the four perspectives and their interactions. These perspectives will be the basis on which we will build our model. In what follows, we look deeper into each one of them and construct a system dynamics model.

Figure 3.1 LAU BSC Model

3.2 System Dynamics Model

Figure 3.2 shows a simple stock and flow diagram of our system. Note that the Faculty-to-Student Ratio (FSR) is nothing but the inverse of the SFR.

Figure 3.2 Simple Stock and Flow Diagram

3.2.1 Faculty Population

Since the resources allocation is directly related to the Faculty Population, it is more convenient to start by modeling it first.

As mentioned above, a typical faculty body comprises three different faculty ranks: Assistant Professors (on tenure track), Associate Professors (tenured) and Full Professors (tenured). A fourth rank is defined as Distinguished Professors: Senior Professors who have proven academic and research excellence.

This model should be further elaborated since each rank earns a different salary. The higher the rank, the higher the salary. We furthermore explained that the research productivities of different faculty ranks likewise differ, mainly due to tenure. Assistant Professors on tenure track are usually highly productive while on the other hand Associate and Full professors are not. Distinguished Professors are also highly productive, since, as the name indicates, they excelled in their research and need no motivation to keep on being productive.

Now it is important to know how these different ranks interact, that is, what are the promotion policies. Typically, assistant professors either get tenured or leave. Tenured staff are either promoted to a higher rank or stay in the same rank. The promotion rate is dictated by the productivity of the rank i.e. the higher the productivity of Associate Professors, the higher the number of promotions to Professors and vice versa. Let us note that a tenured faculty member can retire at any rank or leave due to retention failure. This being said, we can start building a relatively accurate Faculty Population model as shown in Figure 3.3.

Figure 3.3 Faculty Population

Productivities are defined as positive normalized numbers (from 0 to 1), 0 being the least productive and 1 being the most. They depend on the amount of funds dedicated for research. The productivity of Assistant and Distinguished Professors is considered to be 1.

The Tenure Rate is nothing but the rate of yearly Promotions from Assistant to Associate Professors. This rate can be found statistically over several years.

The Associate to Full Promotion Rate is the yearly rate of promoting Associates to Full Professors, providing their productivity becomes 1.

The Full to Distinguished Promotion Rate is similar to the Associate to Full Promotion Rate, but is relative to the Full Professors Population.

The Retirement and Retention Rate is the yearly rate at which Faculty members retire or leave. This rate can also be found statistically by the organization and is considered to be constant for all faculty ranks.

This model shows clearly how promotions are affected. The Promoted to Associate Professor depends on the Tenure Rate. However since it is only a rate, it should be multiplied the number of Assistant Professors to find the actual number of promotions. This explains the existing link between Assistant Professors and Associate Professors. Note that this promotion does not depend on the Assistant Professors Productivity since it is considered to be always 1.

On the other hand, Promoted to Full Professor and Promoted to Distinguished Professor depend on a certain constant rate (Associate to Full and Full to Distinguished Promotion Rates) and also on their respective productivities. That is, the Promoted to Full Professor is proportional to the Productivity of Associate Professors. The same goes for Full Professors.

The number of retired faculty members in each rank is nothing but the product of the Retirement and Retention Rate, and the actual number of faculty members in each rank.

Before writing the dynamic equations, it is important to further analyze the distribution of faculty members in each rank. For example, let us look at the Assistant Professors Population. Consider we initially have 120 Assistant Professors and the Tenure rate was found to be 30% per year. This does not mean that 36 Faculty members will get promoted, however 30% of the assistant professors eligible for promotion will actually get it. The university's policy states that an Assistant Professor is eligible for promotion after his sixth year in this rank. In order to determine the number of eligible members, let us consider the population to be uniformly distributed over this six years. The number of eligible members becomes $120/6=20$ members per year. Thus, only 30% of these 20 will get promoted, which results in 6 new Associate Professors. The other 14 will leave the university. Furthermore, assume 30 new faculty members are joining the university. The total number of Assistant Professors in the next year will become the actual number this year, minus the number of leaving and promoted faculty, plus the number of new faculty. This results in the new number of Assistant Professors to be $120 - 20 + 30 = 130$. We can clearly see that their number increased by 10 from the original number. Now let us look at the new number of promotions for the following year. Just as before, the number of newly appointed Associate Professors = $(130/6)*0.3 = 6.5$. It can clearly

be seen that a portion of the new faculty joining the university has been promoted in the following year, which is totally unrealistic. The same applies to other ranks

Therefore the model as it is cannot be used to accurately describe the system. It has to reflect the delay existing from being newly appointed to being eligible for promotion. Typically, this delay is six years. Figures 3.4, 3.5, 3.6 and 3.7 show how the detailed Assistant, Associate, Full and Distinguished Professors Population (respectively) become.

Figure 3.4 Detailed Assistant Professors Population Model

Figure 3.5 Detailed Associate Professors Population Model

Figure 3.6 Detailed Full Professors Population Model

Figure 3.7 Detailed Distinguished Professor Population Model

The six year path to promotion can be clearly seen in the first three figures above. Each year, all professors move to the next year category, until they reach year 6. At year 6, they either get promoted or not. In the case of Assistant Professors, the members that do not get promoted

leave the university. In the case of Associate and Full Professors, if they are not promoted, they either retire or stay as Associate or Full professors. Therefore the 6th Year Associate or Full Professors actually include members that have been for six years or above in the same rank.

This also applies to Distinguished Professors; however, since they cannot be promoted anymore, we simply differentiate between first year and more than 1 year Distinguished Professors.

Finally, it is important to note that the Promoted Assistant Professors flowing out of the Assistant Professors Population is nothing but the one flowing in to the Associate Professors Population. The same applies for Promoted Associate Professors and Promoted Full Professors.

After building a clear understanding of the faculty population, we can start writing the dynamic equations describing this part of the system.

3.2.1.1 Dynamic Equations of Assistant Professors Population

As mentioned above, figure 3.4 depicts the detailed model of the Assistant Professors Population. Also, we stated that all members in the i^{th} year category (1st Year Assistant Professors, 2nd Year Assistant Professors ...) will move to the $i+1^{\text{th}}$ year category in the next time step. This basically means that the faculty members are aging in the rank. It is important to note that the time step we consider for this system is one year, since all promotions and hiring happen on a year to year basis. Assuming we are initially at year “k”, we can write the following equations:

$$\begin{aligned} &1st\ Year\ Assistant\ Professors_{k+1}(members) \\ &= New\ Faculty_k\left(\frac{members}{year}\right) \times \Delta k(years) \end{aligned} \quad (3.1)$$

$$\begin{aligned} &1st\ to\ 2nd\ Year\ Assistant_k\left(\frac{members}{year}\right) \\ &= 1st\ Year\ Assistant\ Professors_k(members) \\ &\quad / \Delta k(years) \end{aligned} \quad (3.2)$$

$$\begin{aligned}
& \text{2nd Year Assistant Professors}_{k+1}(\text{members}) \\
&= \text{1st to 2nd Year Assistant}_k\left(\frac{\text{members}}{\text{year}}\right) \times \Delta k(\text{years})
\end{aligned} \tag{3.3}$$

Where Δk in our case is 1 year. Replacing (3.2) in (3.3), we get:

$$\text{2nd Year Assistant Professors}_{k+1} = \text{1st Year Assistant Professors}_k \tag{3.4}$$

The same applies to other year categories and we can deduce the following equations:

$$\begin{aligned}
& \text{3rd Year Assistant Professors}_{k+1} \\
&= \text{2nd Year Assistant Professors}_k
\end{aligned} \tag{3.5}$$

$$\text{4th Year Assistant Professors}_{k+1} = \text{3rd Year Assistant Professors}_k \tag{3.6}$$

$$\text{5th Year Assistant Professors}_{k+1} = \text{4th Year Assistant Professors}_k \tag{3.7}$$

$$\text{6th Year Assistant Professors}_{k+1} = \text{5th Year Assistant Professors}_k \tag{3.8}$$

We also explained above that the number of Promoted to Associate Professors is dictated by the Tenure Rate. Therefore:

$$\begin{aligned}
& \text{Promoted Assistant Professors}_k\left(\frac{\text{members}}{\text{year}}\right) \\
&= \text{6th Year Assistant Professors}_k(\text{members}) \\
&\times \text{Tenure Rate}\left(\frac{\text{members}}{\text{members} \times \text{years}}\right)
\end{aligned} \tag{3.9}$$

Since all 6th year Assistant Professors should either get promoted or leave, we can deduce that:

$$\begin{aligned}
 & \text{Non tenured Assistant Professors}_k \left(\frac{\text{members}}{\text{year}} \right) \\
 &= 6\text{th Year Assistant Professors}_k (\text{members}) \\
 &\times (1 - \text{Tenure Rate} \left(\frac{\text{members}}{\text{members} \times \text{years}} \right))
 \end{aligned} \tag{3.10}$$

3.2.1.2 Dynamic Equations of Associate Professors Population

The Associate Professors Population, shown in figure 3.5, is modeled exactly as the Assistant Professors' except for the promotions after year six. We can therefore write the following equations for the first 5 years:

$$\begin{aligned}
 & 1\text{st Year Associate Professors}_{k+1} \\
 &= \text{Promoted to Associate Professors}_k
 \end{aligned} \tag{3.11}$$

$$\begin{aligned}
 & 2\text{nd Year Associate Professors}_{k+1} \\
 &= 1\text{st Year Associate Professors}_k
 \end{aligned} \tag{3.12}$$

$$\begin{aligned}
 & 3\text{rd Year Associate Professors}_{k+1} \\
 &= 2\text{nd Year Associate Professors}_k
 \end{aligned} \tag{3.13}$$

$$4\text{th Year Associate Professors}_{k+1} = 3\text{rd Year Associate Professors}_k \tag{3.14}$$

$$5\text{th Year Associate Professors}_{k+1} = 4\text{th Year Associate Professors}_k \tag{3.15}$$

Note that when we combine (3.10) and (3.11) we get:

$$\begin{aligned}
& \text{1st Year Associate Professors}_{k+1} \\
& = \text{6th Year Assistant Professors}_k \times \text{Tenure Rate}
\end{aligned} \tag{3.16}$$

To understand what happens in the 6th year category, we have to determine what the input and output flows are in that category. We know for sure that all the members in the year 5 category will enter year 6. And we also know that part of the members of year 6 will either get promoted or retire. We can then write:

$$\begin{aligned}
& \text{6th Year Associate Professors}_{k+1} \\
& = \text{6th Year Associate Professors}_k \\
& \quad - \text{Retired Associate Professors}_k \\
& \quad - \text{Promoted to Full Professors}_k \\
& \quad + \text{5th Year Associate Professors}_k
\end{aligned} \tag{3.17}$$

The retiring portion is nothing but the number of Associate Professors in year 6 times the Retirement and Retention Rate.

$$\begin{aligned}
& \text{Retired Associate Professors}_k \\
& = \text{6th Year Associate Professors}_k \\
& \quad \times \text{Retirement and Retention Rate}
\end{aligned} \tag{3.18}$$

The promoted portion is the product of the population in year 6 and the Associate to Full Promotion Rate. Since the actual number of promotions is affected by the productivity of the faculty rank, we should also multiply the latter product by the productivity. That is, the less productive the faculty members are, the less the promotions.

$$\begin{aligned}
& \text{Promoted to Full Professors}_k \\
& = \text{6th Year Associate Professors}_k \\
& \quad \times \text{Associate to Full Promotion Rate} \\
& \quad \times \text{Productivity of Associate Professors}_k
\end{aligned} \tag{3.19}$$

Combining (3.17), (3.18) and (3.19) we get:

$$\begin{aligned}
 6th\ Year\ Associate\ Professors_{k+1} = & 6th\ Year\ Associate\ Professors_k \\
 & \times (1 - Associate\ to\ Full\ Promotion\ Rate \\
 & \times Productivity\ of\ Associate\ Professors_k \\
 & - Retirement\ and\ Retention\ Rate) \\
 & + 5th\ Year\ Associate\ Professors_k
 \end{aligned} \tag{3.20}$$

Note that in years 1 to 5, all faculty members leave one category to move to the next. However in the case of the 6th year Associate Professors category, some of them will stay in year 6 and therefore should be added to the new number of members in this category. Also note that the term Δk and the units were dropped for simplification.

The only remaining variable to identify is the productivity of Associate Professors. We know that it is a function of the Funds Dedicated for Research for Associate Professors. We also defined it to be a positive number between 0 and 1. Common sense says that the more funds we dedicate, the higher the productivity would be. Also, in the case of no funds at all, it would be impractical to consider that the productivity drops to 0. It has therefore a minimum value greater than 0. Figure 3.8 below shows how we modeled Research Productivity in function of the Dedicated Funds for Research for Associate Professors.

Figure 3.8 Research Productivity vs. Research Funds for Associate Professors

This productivity model might not be accurate enough to describe the actual relationship between funds and research productivity. Ideally, other variables should also be considered such as different resources for research (labs availability, equipment, graduate students ...) but in this thesis, we will consider all these variables as being part of the funds. Note that the productivity curve satisfies the conditions we set earlier.

3.2.1.3 Dynamic Equations of Full Professors Population

The Full Professors Population is modeled exactly as the Associate Professors model. The equations for this part of the system become:

$$1st\ Year\ Full\ Professors_{k+1} = Promoted\ to\ Full\ Professors_k \quad (3.21)$$

$$2nd\ Year\ Full\ Professors_{k+1} = 1st\ Year\ Full\ Professors_k \quad (3.22)$$

$$3rd\ Year\ Full\ Professors_{k+1} = 2nd\ Year\ Full\ Professors_k \quad (3.23)$$

$$4th\ Year\ Full\ Professors_{k+1} = 3rd\ Year\ Full\ Professors_k \quad (3.24)$$

$$5th\ Year\ Full\ Professors_{k+1} = 4th\ Year\ Full\ Professors_k \quad (3.25)$$

In the case of Associate Professors, we can see that even if there were no funds available for research, some members would still get promoted to Full Professors. This however does not apply for promotion from Full to Distinguished Professors since initially there are no Distinguished Professors. Looking at the Faculty Body at LAU, we know that there is no Distinguished Professor rank. Ideally this rank should exist, if there were funds dedicated for research. Therefore, if there were no research funds, no Full Professors are promoted to Distinguished Professors. But this does not mean that their productivity will also be zero. In fact, the Productivity curve of Full Professors is shown in Figure 3.9.

Figure 3.9 Research Productivity vs Research Funds for Full Professors

This graph shows that the productivity function of Full professors satisfies the conditions specified above. For zero funds, the productivity is 0.15. This will help define the number of promoted to distinguished professors in function of the productivity. Consider equation (3.26) below:

$$\begin{aligned}
 & \textit{Promoted to Distinguished Professors}_k \\
 &= \textit{6th Year Full Professors}_k \\
 &\times \textit{Full to Distinguish Promotion Rate} \\
 &\times (\textit{Productivity of Full Professors}_k - 0.15)
 \end{aligned} \tag{3.26}$$

We can see that the equation of Promoted to Distinguished Professors is similar to the one of Promoted to Full Professors, however we subtracted Productivity(0)=0.15 from the overall productivity. This is to make sure that if no funds are being dedicated to research, no promotions will happen. We can therefore derive the 6th Year Full Professors equation shown in (3.27).

$$\begin{aligned}
 & \textit{6th Year Full Professors}_{k+1} = \textit{6th Year Full Professors}_k \\
 &\times [1 - \textit{Full to Distinguished Promotion Rate} \\
 &\quad \times (\textit{Productivity of Full Professors}_k - 0.15) \\
 &\quad - \textit{Retirement and Retention Rate}) \\
 &\quad + \textit{5th Year Full Professors}_k]
 \end{aligned} \tag{3.27}$$

3.2.1.4 Dynamic Equations of Distinguished Professors Population

This is the most trivial part of the Faculty Population. We can clearly see that all 1st year Distinguished professors are moved to "> 1 year Distinguished Professors" in the next year. Since they cannot be promoted any further, the only members leaving the Distinguished Professors Population are the Retired Distinguished Professors. We can therefore write the following equations:

$$\begin{aligned}
& 1st\ Year\ Distinguished\ Professors_{k+1} \\
& = Promoted\ to\ Distinguished\ Professors_k
\end{aligned}
\tag{3.28}$$

$$\begin{aligned}
& > 1\ Year\ Distinguished\ Professors_{k+1} \\
& = > 1\ Year\ Distinguished\ Professors_k \\
& \times (1 - Retirement\ and\ Retention\ Rate) \\
& + 1st\ Year\ Distinguished\ Professors_k
\end{aligned}
\tag{3.29}$$

Note that, as shown in figure 3.4, the total number of Assistant Professors is nothing but the sum of the number of Assistant professors in each rank. The same applies for Associate (figure 3.5), Full (figure 3.6) and Distinguished (figure 3.7) Professors. Now that the detailed model of the faculty population has been explained, we can move on to see how it affects the scholarly reputation.

3.2.2 Scholarly Reputation Model

As mentioned earlier, worldwide university ranking agencies mostly rely on research productivity and FSR. Figure 3.10 shows how Times Higher Education and QS rating agencies compute the impact of research productivity on the scholarly reputation of the university. Figure 3.11 shows how we approximated this impact. This approximation can be considered accurate enough to be used in our simulations. The other main contributor on the reputation is the FSR. Figure 3.12 shows how the FSR impacts the scholarly reputation and figure 3.13 how we approximated it to be able to include it in our simulations.

Figure 3.10 Scholarly Reputation vs Research Productivity

Figure 3.11 Actual and Approximated Scholarly Reputation vs Research Productivity

Figure 3.12 Impact of FSR on Scholarly Reputation

Figure 3.13 Actual and Approximated Scholarly Reputation vs FSR

In this thesis, we will consider the impact of research on the scholarly reputation to be 70% and the 30% would be from the impact of the FSR. The following example illustrates how the overall scholarly reputation is calculated. Consider that the research productivity was found to be 0.4 and the FSR 0.5. Looking at figures 3.11 and 3.13, we can see that the scholarly reputation for a productivity of 0.4 and FSR of 0.5 are 0.6 and 0.1 respectively. Therefore the overall scholarly reputation would be $0.7 \times 0.6 + 0.3 \times 0.1 = 0.45$.

The FSR is easy to calculate. It is the actual number of Faculty members over the actual number of students. This ratio is also normalized by the nominal FSR, which is considered to be $\frac{1}{20}$. This value is chosen arbitrarily.

The research productivity on the other hand has a more complex relation to the system variables. It is actually the weighted sum of different faculty rank productivities.

$$\begin{aligned}
 &\textit{Overall Research Productivity} \\
 &= (\textit{Productivity of Assistant Professors} \\
 &\quad \times \textit{Number of Assistant Professors} \\
 &\quad + \textit{Productivity of Associate Professors} \\
 &\quad \times \textit{Number of Associate Professors} \\
 &\quad + \textit{Productivity of Full Professors} \\
 &\quad \times \textit{Number of Full Professors} \\
 &\quad + \textit{Productivity of Distinguished Professors} \\
 &\quad \times \textit{Number of Distinguished Professors}) \\
 &\quad / \textit{Total Number of Faculty Members}
 \end{aligned} \tag{3.30}$$

Since the Assistant and Distinguished Professors have a productivity of 1, the equation could be further simplified to:

Overall Research Productivity

$$\begin{aligned} &= (\text{Assistant Professors} \\ &+ \text{Productivity of Associate Professors} \\ &\times \text{Associate Professors} \\ &+ \text{Productivity of Full Professors} \times \text{Full Professors} \\ &+ \text{Distinguished Professors}) \\ &/ \text{Total Number of Faculty Members} \end{aligned} \quad (3.31)$$

Where the “Number of” were dropped to simplify the equation.

It is important to remember that the Productivity of Associate Professors and the Productivity of Full Professors depend only on the Funds Dedicated for Research for Associate and Full Professors respectively.

We can therefore deduce the causal loop diagram shown in figure 3.14 relating the faculty population to the scholarly reputation.

Figure 3.14 Causal loop diagram of Scholarly Reputation

3.2.3 Student Population Model

Figure 3.2 in the beginning of the chapter shows the student population as a stock with a certain inflow rate of new students and outflow of graduating students. The number of new students enrolling yearly is affected by the scholarly reputation of the university. The number of graduating students is however the result of an internal process that will be discussed in the following section.

One way of determining the number of graduating students would be to divide the number of students by the average time to get a degree. However, just like the case of faculty ranks, a portion of the new students enrolling in a certain year would graduate the next. We should

therefore account for the path to graduation. Since a medical degree requires the most time to complete, we will consider the path to be maximum seven years long. A university student can graduate at any year in this path. We will denote by $P(\text{grad } 1)$, $P(\text{grad } 2)$, $P(\text{grad } 3)$..., $P(\text{grad } 7)$, the probabilities of a student graduating at year 1, 2, 3,...,7, respectively, such as:

$$\begin{aligned} & (\text{Number of graduating students at year } i)_k \\ &= (\text{Number of students in year } i)_k \times P(\text{grad } i) \end{aligned} \quad (3.32)$$

The model of the student population is shown in figure 3.15.

Figure 3.15 Student Population

The Completed Degree in i Years rates are nothing but the Number of Graduating Students at year i defined in equation (3.32). The Number of students in year i are the i^{th} Year Students stocks depicted in figure 3.15. Therefore, the number of $i+1^{\text{th}}$ Year Students which is equal to the number of students going from year i to year $i+1$ (1^{st} to 2^{nd} , 2^{nd} to 3^{rd} , 3^{rd} to 4^{th} ...) becomes:

$$i + 1^{th} Year Students_{k+1} = i^{th} Year Students_k \times (1 - P(grad\ i)) \quad (3.33)$$

We can consequently write the following equations:

$$1^{rst} Year Students_{k+1} = New Students_k \quad (3.34)$$

$$2^{nd} Year Students_{k+1} = 1^{st} Year Students_k \times (1 - P(grad\ 1)) \quad (3.35)$$

$$\begin{aligned} 3^{rd} Year Students_{k+1} \\ = 2^{nd} Year Students_k \times (1 - P(grad\ 2)) \end{aligned} \quad (3.36)$$

$$\begin{aligned} 4^{th} Year Students_{k+1} \\ = 3^{rd} Year Students_k \times (1 - P(grad\ 3)) \end{aligned} \quad (3.37)$$

$$5^{th} Year Students_{k+1} = 4^{th} Year Students_k \times (1 - P(grad\ 4)) \quad (3.38)$$

$$6^{th} Year Students_{k+1} = 5^{th} Year Students_k \times (1 - P(grad\ 5)) \quad (3.39)$$

$$7^{th} Year Students_{k+1} = 6^{th} Year Students_k \times (1 - P(grad\ 6)) \quad (3.40)$$

Now, it is important to understand why the interaction between Scholarly Reputation and the number of New Students is modeled this way. As we mentioned earlier, the number of New Students enrolling yearly is affected by the reputation of the university. The **change** in the new number of students is proportional to the **change** in reputation from year to year. This explains the University Scholarly Reputation at year k-1 stock that only holds the previous reputation in order to compute the difference in reputation from year to year. This difference is modeled by:

$$\begin{aligned}
& (\text{University Scholarly Reputation at year } k) \\
& - (\text{University Scholarly Reputation at year } k - 1)
\end{aligned} \tag{3.41}$$

Therefore the change in number of new students becomes:

$$\begin{aligned}
& \text{Change in Nmber of new students} \\
& = [(\text{University Scholarly Reputation at year } k) \\
& - (\text{University Scholarly Reputation at year } k - 1)] \\
& \times \text{Gain in Students}
\end{aligned} \tag{3.42}$$

Where Gain in Students is the sensitivity of the change in reputation on the change in number of “New Students”.

This being said, the number of New Students becomes:

$$\begin{aligned}
& \text{New Students}_k \\
& = \text{Change in Number of new students}_k \\
& + 1^{\text{st}} \text{ Year Students}_k
\end{aligned} \tag{3.43}$$

Combining equations (3.34), (3.42) and (3.43), we get:

$$\begin{aligned}
& 1^{\text{st}} \text{ Year Students}_{k+1} \\
& = 1^{\text{st}} \text{ Year Students}_k \\
& + [(\text{University Scholarly Reputation at year } k)_k \\
& - (\text{University Scholarly Reputation at year } k - 1)_k] \\
& \times \text{Gain in Students}
\end{aligned} \tag{3.44}$$

The Reset University Reputation at year k-1 rate is used to ensure that no accumulation is occurring. That is:

$$\begin{aligned}
& \text{Reset University Reputation at year } k - 1 \\
& = \text{University Scholarly Reputation at year } k - 1
\end{aligned} \tag{3.45}$$

Before proceeding to model the last part of the system, it is important to explain how the probabilities $P(\text{grad } 1)$, $P(\text{grad } 2)$,... can be obtained. Statistically, one can calculate the probability of a new student graduating at a given year. This would depend on the major the student has enrolled in.

Looking at previous years, we can therefore determine the probability distribution of the “time to complete degree” variable. Let’s denote by $P(i \text{ years})$, the probability of a new student graduating in i years. For example, if 10 new students joined LAU, the fraction of these students graduating after 4 years is equal to 10 times $P(4 \text{ years})$. In our model, however, the number of graduating students at year 4 is actually the number of 4th year students times $P(\text{grad } 4)$ (probability of 4th years students graduating this year). We can therefore see that $P(4 \text{ years}) \neq P(\text{grad } 4)$. $P(\text{grad } 4)$ is therefore the probability of graduating in 4 years divided by the probability of not graduating in previous years. The probability of graduating in the previous years is nothing but the sum of probabilities of graduating in each previous year. We can therefore write the following relationship:

$$P(\text{grad } i) = \frac{P(i \text{ years})}{1 - \sum_{l=1}^{i-1} P(l \text{ years})} \tag{3.46}$$

3.2.4 Financial Model

As mentioned at the beginning of the chapter, the tuition fees are the source of revenues considered in this thesis. This can be calculated by multiplying the number of students by the average tuitions fee, which can be statistically calculated.

The costs considered are the salaries and overhead of faculty members and the funds dedicated for research. The financial model is depicted in figure 3.16. The equations of this model are given as:

$$\text{Revenues} = \text{Total Number of Student} \times \text{Average Tuition Fee} \quad (3.47)$$

$$\begin{aligned} \text{Costs} = & \text{Assistant Professors} \times \text{Salary of an Assistant Professor} + \\ & \text{Associate Professors} \times (\text{Salary of an Associate Professor} + \\ & \text{Funds Dedicated for Research for Associate Professors}) + \\ & \text{Full Professors} \times \quad (3.48) \\ & (\text{Salary of a Full Professor} + \\ & \text{Funds Dedicated for Research for Full Professors}) + \\ & \text{Distinguished Professors} \times \text{Salary of a Distinguished Professor} \end{aligned}$$

$$\text{Balance} = \text{Revenues} - \text{Costs} \quad (3.49)$$

3.3 Conclusion

In this chapter we constructed the system dynamics model of LAU. We based the model on the four BSC perspectives. In the first modeling iteration, we identified the major parts of the system and their interactions. Next, we expanded each of these parts to extract an accurate and relevant model. All the dynamic equations were then formulated.

In what follows, we will define the system inputs, outputs, identify all the parameters and conduct a situation analysis in order to find the initial conditions.

Figure 3.16 Financial Model

Chapter Four

Simulation of the LAU System Dynamics Model

In this chapter we identify the inputs and outputs of the system and assign values for the system parameters. Finally we present numerical simulations to assess the behavior of the system.

4.1 System inputs

In the BSC model presented earlier, the recruitment of new faculty, dedication of funds for research for faculty at associate professor rank and for faculty at professor rank are considered to be the control policies.

Table 4.1 Input variables of SD model

Input	Variable name	Units
1	New Faculty	faculty per year
2	Funds Dedicated for Research for Associate Professors	k\$ per faculty per year
3	Funds Dedicated for Research for Full Professors	k\$ per faculty per year

4.2 System outputs

Since we are simulating an SD model, we can monitor all desired variables. However in accordance with the BSC measures specified earlier, the outputs will be defined as:

Table 4.2 Output variables of SD model

Output	Variable name	Units
--------	---------------	-------

1	1 st Year Students (number of new students enrolling yearly at LAU)	students per year
2	Faculty to Student Ratio	faculty per student
3	Productivity of Associate Professors	dimensionless
4	Productivity of Full Professors	dimensionless

4.3 System Parameters

Tables 4.3, 4.4 and 4.5 show the values of the system parameters used in the simulation.

Table 4.3 System Parameters of Faculty Population

Parameter	Value	Unit	Derivation
Retirement and Retention Rate	0.15	Year ⁻¹	estimation
Tenure Rate	0.65	Year ⁻¹	estimation
Associate to Full Promotion Rate	0.15	Year ⁻¹	estimation
Full to Distinguished Promotion Rate	0.05	Year ⁻¹	estimation

Table 4.4 Systems Parameters of Student Population

Parameter	Value	Unit	Derivation
P(grad 1)	0	Year ⁻¹	LAU website
P(grad 2)	0	Year ⁻¹	LAU website
P(grad 3)	0.653	Year ⁻¹	LAU website
P(grad 4)	0.510	Year ⁻¹	LAU website
P(grad 5)	0.473	Year ⁻¹	LAU website

P(grad 6)	0.756	Year ⁻¹	LAU website
P(grad 7)	1	Year ⁻¹	LAU website
Gain in Students	2200	Student per year	estimation

Table 4.5 System Parameters of Financial Model

Parameter	Value	Unit	Derivation
Average Tuition Fee	14	k\$ per year	estimation
Salary of an Assistant Professor	70	k\$ per year	estimation
Salary of an Associate Professor	90	k\$ per year	estimation
Salary of a Full Professor	120	k\$ per year	estimation
Salary of a Distinguished Professor	130	k\$ per year	estimation

Table 4.6 shows the different nonlinear functions equation used in the model.

Table 4.6 Variable Modeling Functions

Variable	Equation	Unit	Derivation
Productivity of Associate Professors	$1 - 0.8e^{\frac{\text{Input 2}}{5}}$	dimensionless	estimation (figure 3.8)
Productivity of Associate Professors	$1 - 0.85e^{\frac{\text{Input 3}}{7}}$	dimensionless	Estimation (figure 3.9)

Scholarly Reputation	$0.7 \left(1 - \frac{1}{1 + 0.2e^{\left(\frac{(Research\ Productivity - 0.25)}{0.07} \right)}} \right)$		dimensionless	estimation
	$+ 0.3 \left(\frac{Faculty\ to\ Student\ Ratio}{0.62} - 0.65 \right)$			
Nominal				
Faculty to Student Ratio	0.2	faculty per student		estimation

4.4 Initial Values

Few measures were available on the LAU website, shown in table 4.7

Table 4.7 Facts and Figures from LAU website

Figure	Value
Total Number of Students	8146
Number of Assistant Professors	113
Number of Associate Professors	84
Number of Professors	33

A first run simulation was performed in order to obtain desirable figures shown in table 4.7. The results are shown in table 4.8.

Table 4.8 Initial Stock Values

Stock	Value
1 st Year Students	2200
2 nd Year Students	2200
3 rd Year Students	2200
4 th Year Students	763
5 th Year Students	374
6 th Year Students	197
7 th Year Students	48
1 st Year Assistant Professors	8
2 nd Year Assistant Professors	8
3 rd Year Assistant Professors	8
4 th Year Assistant Professors	8
5 th Year Assistant Professors	8
6 th Year Assistant Professors	8
1 st Year Associate Professors	5
2 nd Year Associate Professors	5
3 rd Year Associate Professors	5
4 th Year Associate Professors	5
5 th Year Associate Professors	6
6 th Year Associate Professors	86
1 st Year Full Professors	3
2 nd Year Full Professors	2
3 rd Year Full Professors	3
4 th Year Full Professors	2
5 th Year Full Professors	3

6th Year Full Professors	75
1st Year Distinguished Professors	0
>1 Year Distinguished Professors	0
Scholarly Reputation	0.242

The initial input is shown in table 4.9

Table 4.9 Initial Inputs

Input	Value
1	8
2	0
3	0

4.5 Simulation

The simulations results over 50 years for the input given in table 4.9 are shown in figure 4.2.

It can be seen that the system is stable. Assume we wish to target an enrollment rate of 3000 new students per year and a 0.05 FSR. Figure 4.2 shows the simulation results for a constant hiring rate of 20 new faculty per year, a research fund rate of 5 k\$ per faculty per year for associate professors and a 7k\$ per capita per year for associate professors, in attempt of achieving the specified goals.

Although the productivities of associate and full professors and the total number of faculty members have increased, it could not track the desired FSR. The hiring rate is then set to 30, and the results are shown in figure 4.3

The FSR increased to reach a value of 0.04 after 30 years, while the number of new students remains around 3000. This shows that it is impossible to design policies by trial and error, since the behavior of the system is sometimes non-intuitive.

Figure 4.1 SD model Simulation results

Figure 4.2 Simulation Result of SD model (different input values)

Figure 4.3 Simulation Result of SD model with a hiring rate of 30

4.6 Conclusion

In this chapter we defined the inputs and outputs of the system relevant to the BSC model. We then assigned values for the system parameters and identified the initial stock values through a first run simulation.

The simulation of the model indicated that the system is stable; however designing decision policies using a simulation based approach is impossible. In the next chapter we propose design a MIMO PID for the system and assess the simulation results.

Chapter Five

PID Controller Design

In this chapter we will apply a PID controller to the system. As mentioned in chapter 2, designing the controller relies on the state, input and output matrices, which do not exist in the system dynamics model. In what follows, we will convert the system dynamics model obtained in chapter 3 into a state-space model, based on the process proposed in chapter 2. Once the state, input and output matrices are identified, we will design a PID controller that will replace the conventional decision making process: the system analyst.

5.1 State Space Equations

In Chapter 2 we saw how to convert a System Dynamics model into state space equations. The stocks and their dynamics equations are defined as the state variables and the state space equations respectively.

Referring to figures 3.4, 3.5, 3.6, 3.7 and 3.15, we define the set of state variables:

$$X = (x_1, x_2, x_3, x_4, \dots, x_{28})^T$$

And the set of input variables:

$$U = (u_1, u_2, u_3)^T$$

Such that:

$$x_1 = 1^{st} \text{ Year Students}$$

$$x_2 = 2^{nd} \text{ Year Students}$$

$$x_3 = 3^{rd} \text{ Year Students}$$

$$x_4 = 4^{th} \text{ Year Students}$$

$$x_5 = 5^{th} \text{ Year Students}$$

$$x_6 = 6^{th} \text{ Year Students}$$

$$x_7 = 7^{th} \text{ Year Students}$$

$x_8 = 1^{st} \text{ Year Assistant Professors}$
 $x_9 = 2^{nd} \text{ Year Assistant Professors}$
 $x_{10} = 3^{rd} \text{ Year Assistant Professors}$
 $x_{11} = 4^{th} \text{ Year Assistant Professors}$
 $x_{12} = 5^{th} \text{ Year Assistant Professors}$
 $x_{13} = 6^{th} \text{ Year Assistant Professors}$
 $x_{14} = 1^{st} \text{ Year Associate Professors}$
 $x_{15} = 2^{nd} \text{ Year Associate Professors}$
 $x_{16} = 3^{rd} \text{ Year Associate Professors}$
 $x_{17} = 4^{th} \text{ Year Associate Professors}$
 $x_{18} = 5^{th} \text{ Year Associate Professors}$
 $x_{19} = 6^{th} \text{ Year Associate Professors}$
 $x_{20} = 1^{st} \text{ Year Full Professors}$
 $x_{21} = 2^{nd} \text{ Year Full Professors}$
 $x_{22} = 3^{rd} \text{ Year Full Professors}$
 $x_{23} = 4^{th} \text{ Year Full Professors}$
 $x_{24} = 5^{th} \text{ Year Full Professors}$
 $x_{25} = 6^{th} \text{ Year Full Professors}$
 $x_{26} = 1^{st} \text{ Year Distinguished Professors}$
 $x_{27} = > 1 \text{ Year Distinguished Professors}$

$x_{28} = \text{University Scholarly Reputation at year } k - 1$

$u_1 = \text{New Faculty}$

$u_2 = \text{Funds Dedicated for Research for Associate Professors}$

$$u_3 = \text{Funds Dedicated for Research or Full Professors}$$

We can therefore define the set of state equations:

$$F(X, U) = (f_1(X, U), f_2(X, U), f_3(X, U), f_4(X, U), \dots, f_{28}(X, U))^T$$

based on equations (3.1) to (3.45), such that:

$$f_1 = x_1 \left(\frac{0.484 \sum_{i=8}^{27} x_i}{N_{f2s} \times \sum_{i=1}^7 x_i} + \left(1.43 + 0.00804e \left(\frac{\sum_{i=8}^{13} x_i + \left(1 - 0.8e^{-\frac{u_2}{5}}\right) \sum_{i=14}^{19} x_i + \left(1 - 0.85e^{-\frac{u_3}{7}}\right) \sum_{i=20}^{25} x_i + \sum_{i=26}^{27} x_i}{0.07 \sum_{i=8}^{27} x_i} \right)^{-1} + 0.505 - x_{28} \right) \times 2200 \right)$$

$$f_2 = (1 - P_1)x_1$$

$$f_3 = (1 - P_2)x_2$$

$$f_4 = (1 - P_3)x_3$$

$$f_5 = (1 - P_4)x_4$$

$$f_6 = (1 - P_5)x_5$$

$$f_7 = (1 - P_6)x_6$$

$$f_8 = u_1$$

$$f_9 = x_8$$

$$f_{10} = x_9$$

$$f_{11} = x_{10}$$

$$f_{12} = x_{11}$$

$$f_{13} = x_{12}$$

$$f_{14} = TR \times x_{13}$$

$$f_{15} = x_{14}$$

$$f_{16} = x_{15}$$

$$f_{17} = x_{16}$$

$$f_{18} = x_{17}$$

$$f_{19} = \left(1 - RRR - PR \times \left(1 - 0.8e^{\frac{-u_2}{5}}\right)\right)x_{19} + x_{18}$$

$$f_{20} = PR \times \left(1 - 0.8e^{\frac{-u_2}{5}}\right)x_{19}$$

$$f_{21} = x_{20}$$

$$f_{22} = x_{21}$$

$$f_{23} = x_{22}$$

$$f_{24} = x_{23}$$

$$f_{25} = \left(1 - RRR - DPR \times \left(0.85 - 0.85e^{\frac{-u_3}{7}}\right)\right)x_{25} + x_{24}$$

$$f_{26} = DPR \times \left(0.85 - 0.85e^{\frac{-u_3}{7}}\right)x_{25}$$

$$f_{27} = (1 - RRR)x_{27}$$

$$+ x_{26}$$

$$f_{28} = \frac{0.484 \sum_{i=8}^{27} x_i}{N_{f2s} \times \sum_{i=1}^7 x_i} + \left(1.43 + 0.00804e^{\left(\frac{\sum_{i=8}^{13} x_i + \left(1 - 0.8e^{\frac{-u_2}{5}}\right) \sum_{i=14}^{19} x_i + \left(1 - 0.85e^{\frac{-u_3}{7}}\right) \sum_{i=20}^{25} x_i + \sum_{i=26}^{27} x_i}{0.07 \sum_{i=8}^{27} x_i} \right)^{-1}} \right) + 0.505$$

Where:

- $P_i = P(\text{grad } i)$
- N_{f2s} is the Nominal Faculty to Student Ratio
- TR is the Tenure Rate
- RRR is the Retirement and Retention Rate
- AFR is the Associate to Full Promotion Rate
- FDR is the Full to Distinguished Promotion Rate

We can therefore write the following state space equation:

$$X(k+1) = F(X(k), U(k)) \quad (5.1)$$

In chapter 4 we were looking at several outputs. It is however convenient to look at fewer but significant outputs, and try to steer them to achieve certain desired goals. In fact, the output should be chosen to capture all the measures we need to control. In our case, we define the following outputs:

$$y_1 = 1^{st} \text{ Year Students} = x_1 = h_1(X) \quad (5.2)$$

$$y_2 = \text{Faculty to Student Ratio} = \frac{\text{Number of Faculty}}{\text{Number of Students}} = \frac{\sum_{i=8}^{27} x_i}{\sum_{i=1}^7 x_i} \quad (5.3)$$

$$= h_2(X)$$

Assume $x_{20}(k+1) \approx x_{20}(k)$ we can therefore rewrite f_{20} :

$$f_{20} = x_{20}(k+1) \approx x_{20}(k) = PR \times \left(1 - 0.8e^{\frac{-u_2}{5}}\right) x_{19}(k) \quad (5.4)$$

$$\rightarrow \left(1 - 0.8e^{\frac{-u_2}{5}}\right) = \frac{x_{20}(k)}{PR \times x_{19}(k)} \quad (5.5)$$

Where $\left(1 - 0.8e^{\frac{-u_2}{5}}\right)$ is the Productivity of Associate Professors. We can therefore define:

$$y_3 = \text{Productivity of Associate Professors} = \frac{x_{20}}{PR \times x_{19}} = h_3(X) \quad (5.6)$$

The same applies for f_{26} , and we can write:

$$y_4 = \text{Productivity of Full Professors} = \frac{x_{26}}{DPR \times x_{25}} + 0.15 = h_4(X) \quad (5.7)$$

Let $Y = (y_1, y_2, y_3, y_4)^T$ and $H(X) = (h_1(X), h_2(X), h_3(X), h_4(X))^T$, we can finally write the following state space equations:

$$X(k+1) = F(X(k), U(k)) \quad (5.8)$$

$$Y(k) = H(X(k)) \quad (5.9)$$

It can be seen from the equations above in the chapter, that the system is highly nonlinear. Using the linearization method seen in chapter 2, we can write the following linearized model:

$$X(k + 1) = A(k)X(k) + B(k)U(k) \quad (5.10)$$

$$Y(k) = C(k)X(k) \quad (5.11)$$

Where $A(k) = \frac{\partial F}{\partial X}(k) \Big|_{X_o(k), U_o(k)}$, $B(k) = \frac{\partial F}{\partial U}(k) \Big|_{X_o(k), U_o(k)}$, $C(k) = \frac{\partial H}{\partial X}(k) \Big|_{X_o(k), U_o(k)}$ and

$X_o(k), U_o(k)$ are the operating points. The operating points are nothing but the state variables values and input values of the actual nonlinear system. These values are changing at each point in time therefore matrices A, B and C should be re-evaluated at every time step. Note that

$D(k) = \frac{\partial H}{\partial U}(k) \Big|_{X_o(k), U_o(k)} = 0$, since H is only a function of X . This explains why the outputs

were chosen as follows, otherwise the feed-forward matrix would be different from zero, which makes designing the controller impossible.

Now that we have mapped the system to a multiple-input multiple-output (MIMO) linear time-variant state-space model, we can design an appropriate PID controller.

5.2 Controlled System

The actual process of designing the controller is beyond the scope of the thesis. This work presents a way to map a system dynamics model to a state-space model in order to apply control. Many types of controllers and implementations have been designed for MIMO systems and we are borrowing from these techniques in order to control our MIMO system.

Once the controller has been designed, we will end up with the following system:

Figure 5.1 Controlled System

This figure is similar to figure 2.8 in chapter 2, however the analyst has been replaced by a PID controller and the system dynamics model by the state-space model. The parameters of the PID controller are given by the proportional gain factor K_p , derivative gain factor K_D , and the integral gain factor K_I . The controller output is nothing but the input of the state-space system. We can therefore write:

$$\text{Controller Output} = U(k) = K_p(k)e(k) + K_D\Delta e(k) + K_I \sum e(k)$$

Where $e(k) = Y_d(k) - Y(k)$, is the error between the desired output trajectory $Y_d(k)$ and the actual output $Y(k)$.

It is important to note that, once the controller has been designed, choosing the desired output trajectory is very important for the behavior of the controller. The desired output trajectory should be realizable; otherwise the controller will fail to converge. If, for example, a desired trajectory exceeds the boundary of the system, it will not be tracked properly. Furthermore, since there are multiple outputs, the desired trajectories could contradict one another and this would make the controller fail in tracking the desired output. In some extreme cases, the actual output diverges from the desired one. It is therefore important to choose a realizable desired output trajectory for the controller to track.

Figure 5.2 shows the four outputs of the system along with the total number of students and total number of faculty over 10 years. The simulations were done on MATLAB. The desired output is shown along with the actual output and was set as follows:

$$\text{Desired Number of 1}^{st} \text{ Year Students} = y_{d1} = 3000$$

Desired FSR = $y_{d2} = 0.05$

Desired Associate Professor Productivity = $y_{d3} = 50\%$

Desired Full Professor Productivity = $y_{d4} = 50\%$

Figure 5.2 Controlled System Output

It can be seen from figure 5.2 that all the outputs were perfectly tracked within 10 years. The desired number of 1st year students is approximately met within 5 years. The productivities of Associate and Full Professor exert some overshoot and their rise time is around 4 years. The FSR rises slowly to meet its desired value in 9 years.

Figure 5.3 shows the controller output or $U(k)$. These are the policies that will steer the system towards the desired goals.

Figure 5.3 Controller Output

Looking at the controller output, we can understand the behavior of the actual output of the system. The desired FSR is 0.05, however the initial actual FSR was around 0.03. The controller will therefore increase the number of newly appointed faculty (80 in year 1, 85 in year 2...) in order to decrease the gap between the desired and actual FSR. These new faculty are hired as Assistant Professors, which have a productivity of 1. They will therefore increase the overall productivity. The initial productivities of Associate and Full professors are 0.2 and 0.15 respectively, both below 50%. Therefore the controller will assign more money to increase their productivities, which will in turn increase the overall productivity. This increase along with the improvement of the FSR will lead to an improvement in the scholarly reputation of the

university. This is reflected in the increase in number of students from 2200 to slightly above 2900 from year 3 to year 4. This jump yields to an increase in the total number of students, which reaches 10000 around year 5. From year 1 to 3, both the number of students and the number of faculty were increasing at similar rates. This explains why the FSR stays constant for the first few years. The number of newly appointed faculty peaks at year 3, that is why in the next year the number of faculty jumps from 300 to slightly above 400. The number of students goes from 8500 in year 3 to 9500 in year 5. The improvement in number of faculty within this year ($400/300=1.33$) is greater than the improvement in number of students ($9500/8500=1.12$), which leads to an improvement in FSR.

After year 4, the amount of research funds is decreased to level off the productivities at 50%. When the productivities stabilize, the scholarly reputation will become affected significantly only by the FSR. That is why the number of new students starts to stabilize after year 4 to slightly above 2900. Since the rate of new coming students decreased, the controller will decrease the hiring rate. At year 4, when the hiring rate is first attenuated, the increase in number of students is relatively significant. Therefore the FSR stabilizes again in the next year (5 to 6). After year 5, the number of new students stabilizes almost completely. The number of newly appointed faculty decreases from 53 to 42 in 4 years (year 5 to 9). This positive rate will increase the number of faculty members over these 4 years. Consequently, the FSR will rise again and reach its desired values in year 9.

Figure 5.4 shows the yearly revenues, costs and balance. The revenues are proportional to the total number of students. The costs are mainly affected by the salaries of faculty members. Since their number is increasing, more money is being spent on salaries and on research. The balance increases from year 2 to 6, starting at around 87.5 million \$ and peaking at 109 million \$. It decreases slightly after year 6 to settle at 108 million \$ in year 9.

Figure 5.4 Revenues, Costs and Balance

Figure 5.5 shows the fluctuations in the faculty population. The hiring rate is highest during the first 4 years. That is why the number of Assistant Professors grows almost 5 times from year 1 to 5. After 5 years the number of Assistant Professors keeps on increasing in a slower rate, peaks at 380 in year 8 and decreases back to 300 in year 10. Since there exists a six year delay to go from assistant to associate professor, the increase in number of associate professors starts to show only at year 8. Before that, the number of associates decreased from 110 to 75 due to promotions and retirements. The same applies to the number of full professors, but they cannot be seen to increase within 10 years, due to the 6 year path to promotion. Within these 10 years, some of the full professors were promoted to distinguished professors. Since the

promotion rate is proportional to the productivity of the full professors, we can see that in the first few years it starts high and then begins to decrease after year 5.

Figure 5.5 Controlled System Faculty Population

Figure 5.6 shows how the controller gains vary with time. At first, the proportional and derivative gains jump abruptly in order to respond against the gap between the desired and actual output. After the jump, they start to decrease again since the gap is getting smaller. The integral gain on the other hand starts low (approximately 0), and increases later on to peak at year 4 in order to start eliminating the steady state errors. It then follows the other gains since the error is being reduced.

Figure 5.7 shows the output over a 200 years period. This is only to verify the stability of the controller. The steady-state error is reduced to 0 after 100 years and the system does not fluctuate afterwards.

Note that the glitch in the productivity of associate professors is due to the assumption made in (53).

Figure 5.6 Controller Gains

Figure 5.7 Controlled System Steady State

5.3 Conclusion

In this chapter we mapped the systems dynamics problem into a state-space linear time-variant model and used a PID controller to control it. We then defined a realizable desired output trajectory and analyzed the outputs of the controller which are the inputs of the LAU system. These inputs are the actual policies or strategic plan that will yield to the desired output. Within 10 years, we were able to increase the number of new students from 2200 to 4000, improve the FSR from 0.03 to 0.05 and the productivities of associate and full professors from 0.2 and 0.15 to 0.5. This came at the expense of hiring a lot more faculty in the first few years (around 85 per year) and then level down to around 45 new faculty per year. Also, up to 2.8 k\$ per faculty were spent yearly in the first 4 years on associate professors to increase their productivity. Similarly, a peak of 5.7 k\$ per faculty were spent on full professors.

Chapter Six

Conclusion and Future Work

6.1 Summary

In this thesis, we proposed a new decision making process that borrows from the tactics of a PID controller for correlated multiple-policy multiple-objective system. The policies and measures were determined using the BSC approach. We coupled the BSC with an SD model to capture the dynamics of the system. Designing the controller was achieved by extracting the state matrix from the SD model.

As an application, we considered LAU to be the system at hand. We associated the number of enrolled students, the academic reputation, student-to-faculty ratio and research productivity, and faculty recruitment and faculty development funds with the four BSC perspectives: financial, customer, internal process and learning and growth. The policies under consideration were the number of faculty to be recruited, development funds to be dedicated to faculty at the associate professorial rank, and development funds to be dedicated to faculty at the professorial rank. A 28th-order nonlinear state-space model was constructed in order to reflect the relevant system dynamics. A multiple-input multiple-output (MIMO) Proportional-Integral-Derivative (PID) controller is implemented for shaping the correlated three policies involved in this MPMO system. The associated realizable ten-year target levels were set such that the university reputation is significantly improved, and the overall financial balance is considerably large in order to accommodate for capital expansion. Linearization errors and modeling uncertainties were accounted for in the controller design. Numerical simulations verified the effectiveness of the proposed MPMO systematic approach. The targets were met with virtually no steady-state errors within 9 years.

6.2 Future Work

This study explored many aspects of strategic policy making. Modeling the system and designing the MIMO controller laid the ground for new research areas such as:

1. Conducting a set of interviews and thorough investigations in order to refine the SD model of LAU.
2. Exploring other type of either deterministic or stochastic MIMO controller for the system.
3. Integrating LEEA in the proposed algorithm in order to validate the important measures of the BSC.
4. Integrating the proposed algorithm in system dynamic system analysis tools and computer software.

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