A SYSTEM DYNAMICS APPROACH TO THE SOFTWARE DEVELOPMENT BUSINESS PROBLEM

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ABSTRACT

This thesis focuses on the problem faced by a software development company. Sales have been growing fast throughout the past years, increasing the amount of projects the company has to undertake. The company is concerned that this would affect their ability to finish projects on time and, hence, undermine its future growth.

The author developed a series of Dynamic Hypotheses that may explain the company's fears and hopes. A System Dynamics model was built to gain a better understanding of the structures that support the core hypotheses. Finally, the author developed various analyses and simulations to get an in-depth understanding of the problem.

Specifically, the use of Eigenvalue Elasticity Analysis provided remarkable insights about the model structure and its potential behavior. This led to policy recommendations for the company that can help sustain sales and control the delivery delay.

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INTRODUCTION

A technology company is experiencing problems due to their fast growth in recent years. As they sell more projects, the delivery delay of these projects increases, and the company is concerned on the impact this delay may have in future revenues.

The problem is inherently dynamic, as the number of projects, the project delay, and other variables are in continuous change, reinforcing each other. The concern of the company can not be understood in a static framework, but as dynamic relationships between variables, such as sales and delivery delay.

Therefore, this thesis will study the company's problem using a System Dynamics approach. The author will explore the dynamic structure behind the problem, and will try to understand what the behavior capabilities of this structure are, and how the company can influence this behavior to address its concerns.

In Chapter 1, the author explores the problem as perceived by the company. The company is asked to provide a list of variables that may be relevant to the problem, and to draw their possible evolution over time in what is called “reference modes”, in order to illustrate their hopes and fears regarding the problem. Finally, this chapter lists the policies that the company was planning to implement to solve its problem, prior to the dynamic analysis and recommendations made on this thesis.

In Chapter 2, the author elaborates a set of dynamic hypotheses that may explain the company’s reference modes. The dynamic hypotheses are built from evaluating the effect of some relevant variables on others. These influences among variables form causal loops that can be linked back to the company’s hopes and fears.

Chapter 3 presents a dynamic model of the most interesting hypotheses. This model, composed of integral equations is used to explore whether the behavior captured in the reference modes is compatible with the simplified dynamic structure of the company and market. The model is simulated using computer-based tools and its possible behaviors are contrasted with the company’s assumptions.
In Chapter 4, a sensitivity analysis is performed on the model. This enables a better understanding of how a parameter change may affect the system’s behavior. This analysis is relevant as it not only provides a source for possible policies that the author may recommend to the company, but also it provides an idea on how an error in parameter estimation could affect the model behavior.

In Chapter 5, the author develops an Eigenvalue Elasticity Analysis. This novel approach provides a deeper understanding of the behavioral potential of the model, because of its mathematical structure. As no formal procedures are yet available for the execution of this particular analysis, the reader may find the method herein presented of interest.

Chapter 6 summarizes the main findings from the analysis performed, trying to provide useful recommendations for the company in study. The chapter also comments on the methodology and the future of Eigenvalue Elasticity Analysis.
The Software Development Business Problem

The scenario

An Information Technology company provides its corporate customers with specialized software systems. The Research and Development (R&D) unit of the company undertakes projects to develop these customized software systems. Projects are handled by project managers (PM), who can develop the software by themselves, use internal programmers or external ones.

![](image)

Figure 1.1: Reference mode for projects’ delay

The sales unit is responsible for selling the projects to the customers. This unit also generates a sales forecast. R&D budget is assigned yearly as a fraction of the sales projections. This budget is used to hire the workforce that will work in the projects, as needed.
The concern
Historically, projects at the company have always been late. The amount of delay, however, has been decreasing, as shown in figure 1.1. Management hopes the decreasing trend continues, but fears that it may stop improving.

An additional concern management has regards the project sales. Figure 1.2 shows sales have been growing, and management hopes they will continue to do so. However, they have the fear that sales may drop, because of project delays.

Momentum policies
Before doing this study, the company had some policies in place, and some others were about to be applied. In System Dynamics, those are called momentum policies. One of our interests here is to explore whether these policies are consistent with the dynamic analysis. The ability of testing the policies in a dynamic model of the process can provide valuable insight about the outcome of such policies in reality.
In order to reduce project delay, management plans to implement the following policies:

- Increase the number of project managers
- Hire contractors instead of more internal programmers
- Reduce time spent in administrative tasks
- Encourage the use of formal development methodologies
- Increase number of projects per program manager
- Maintain the number of projects handled by programmers
Dynamic Hypothesis

In this chapter, we will try to explain how the dynamic behavior of the variables in the study can generate the reference modes shown in Chapter 1.

The budget effect

Our first dynamic hypothesis is shown in figure 2.1. If sales grow, then the budget for R&D, which is a percentage of the sales, will also grow. This will enable R&D to hire staff, increasing the workforce as well.

A larger workforce will produce an increase in the working rate. As the working rate increases, the work to do will decrease, and this will reduce the delay. The less delay, the more customer satisfaction.

Figure 2.1: Budget effect causal loop
A higher customer satisfaction will result in a better reputation for the company. This, in turn, will increase sales even more, completing a reinforcing loop.

This virtuous cycle may cause both the sales growth and the delay decrease that the company has been enjoying. If this is the dominating loop, then the management hopes, as stated in Chapter 1, will be more likely than their fears.

![Figure 2.2: Budget and Work-to-do causal loop](image)

**The work-to-do effect**

There are other effects of increasing sales. As sales grow, the amount of work to do will do so as well. The more work to do, the more delay. As delay increases, customer satisfaction will decrease, and so will the company’s reputation. This will decrease sales, completing the balancing loop shown in figure 2.2.
This balancing loop could dominate the reinforcing one in the long term, making management fears likely to happen.

**The contractors effect**

The amount of work to do will determine the required workforce. The relative workforce will be the difference between the existing workforce and the required one.

![Diagram of contractors causal loop](image)

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Figure 2.3: Contractors causal loop

Hence, an increase in work to do will produce an increase in the required workforce. This will reduce the relative workforce, leading to the hiring of contractors.

The more contractors, the more working, and the less work to do. This closes a balancing loop that is shown in figure 2.3.
This loop contributes to the company's hope: The extra load in projects can be handled successfully by hiring contractors.

Hiring more contractors will also reduce the overall skill of the programmers, as the contractors have no experience in the particular project for which they are being hired.

![Diagram of causal loop involving workforce, skill, working, mistakes, work to do, and delay.](image)

Figure 2.4: Contractors and Skill causal loop

Reductions in skill will yield an increase in the mistakes (bugs), which will increase the amount of work to do. As we already saw, this will raise the required workforce, reducing the relative workforce. As relative workforce decreases, more contractors will be hired, closing this time a reinforcing loop, shown in figure 2.4.

This last loop will make the company's fears more likely. Whether the reinforcing loop (+) effect dominates over the balancing one (-) or vice versa is relevant when analyzing the policy of hiring contractors that is now in place to address a growth in the workload.
The overtime effect

Another way to balance a shortage in the relative workforce is to increase the overtime hours. This increases the working rate, so the amount of work to do will decrease. The less amount of work, the lower the required workforce. As the required workforce decreases, the relative workforce increases, and this closes a balancing loop, as shown in figure 2.5.

However, increasing overtime will increase fatigue. This will generate more mistakes, increasing the amount of work to do. This will cause an increase in the required workforce, which leads to a raise in the relative workforce. This will increase the overtime, closing a reinforcing loop (see figure 2.5).

Again, this relates to the reference modes. The balancing (-) loop is making company’s hope most likely, while the reinforcing (+) one can produce the behavior that the company fears.
The combined effect

Combining all the loops presented above, we can get a single causal diagram, which is shown in figure 2.6. We have seen that the loops in the figure can cause both, the feared and the hoped-for behavior. The question is how can we empower the loops that can produce the hoped behavior, and ensure that the detrimental potential behavior does not materialize.

However, before doing that, we want to know if the causal loops we developed could really produce the behaviors described in the reference modes. In the next chapter, we are going to build a dynamic model in order to help us in understanding our hypotheses.
First Model

In order to test our dynamic hypotheses, we are going to build a model. We will begin by modeling one pair of loops and trying to understand them well. As we become comfortable with our analysis, we can add more loops and see whether we get more insight from them or not.

For our first model, we will start by considering just the sales/work-to-do effect, depicted in figure 2.2. This chapter will explore the synthesis of this first model.

Building the model

Let us think of the work in term of projects. The company has a stock of projects to work in, and this stock is fed by project sales, and is depleted by working in the projects and finishing them.

![Diagram of Projects and Workforce stocks and flows](image)

Figure 3.1: Projects and Workforce stocks and flows diagram

The rate at which projects are sold is being determined by the number of sales people and the sales effectiveness, whereas the rate of finishing projects will be driven by the workforce and the productivity, as shown in figure 3.1. In this first model, we are assuming a constant productivity, as we are not considering the overtime and experience effects on it.

The sales effectiveness will be affected by the market perception of delay in project completion, as shown in figure 3.2. We can estimate the delay by comparing the expected project completion time with the average residence time of a project in the projects stock. The latter is calculated by using the
residence time molecule [Hines 1997]. The market perception of the delivery delay is obtained by smoothing the delivery delay with a time constant that we associate to the time to perceive delay.

The actual effect of the perceived delay on sales effectiveness is estimated as shown in figure 3.3. If there is no delay, the sales effectiveness will be the normal sales effectiveness. As the perceived delay increases, salespeople find it more difficult to sell new projects, because of the bad reputation that the company has. The opposite happens if the company becomes known for finishing the projects early. We assumed the function to saturate, as we believe that the delay can not affect the sales effectiveness beyond certain point.
Figure 3.3: Effect of perceived delay on sales effectiveness

Note that most system dynamicists would recommend the use of a first order control for the finishing projects rate, in order to prevent the projects stock from becoming negative. However, we do not plan to work close to the boundary of an almost-empty Projects stock. Hence, we decided not to add the extra complexity of an additional loop that is not going to be needed within the boundaries of the study. The alternative of adding a minimum finishing projects rate based in the integration period looks even less elegant than the absence of a non-negativity control in the author's opinion. It is important, however, to keep this deficiency of the model in mind at all times, and add the necessary structure should the projects stock ever become close to zero.

Now let us look at the workforce dynamics. The workforce is fed by the hiring/firing rate. We are modeling it as a smooth of the indicated workforce.

The indicated workforce calculation is based upon two variables: The needed workforce and the affordable workforce. The former is computed as the number of projects outstanding, times the target project duration, divided by the productivity (PDY), whereas the latter depends on the budget, as shown in figure 3.4.
In the company of study, the R&D budget is determined yearly as a fraction of the sales forecast. We can represent this situation by using the extrapolation module [Hines 1997], as shown in figure 3.5. The actual revenues are smoothed to get the perceived revenues, which are averaged over the duration over which to calculate trend. The relation between these two variables gives us a fractional trend, which is in turn used to get a forecast of expected revenues over a forecast horizon.
There are two sources of revenue. Up-front revenues come from selling projects. It is a fraction of the project price. The rest comes upon finishing the project, as shown in figure 3.6.
Putting it all together, we get the fourth order model shown in figure 3.7. The model equations are listed in Appendix A.

Equilibrium
Is it possible for this model to achieve a non-trivial steady state? Let us try to find what conditions need to be satisfied for this to happen.

If we look at the projects stock, in steady state the rate at which we sale projects should be equal to the rate of finishing them:

\[ \text{SellPrj} = \text{FinishPrj} \]

\[ \Leftrightarrow \text{SalesPeople} \times \text{SalesEff} = \text{Workforce} \times \text{PDY} \]

\[ \Leftrightarrow \text{SalesPeople} \times \text{EDoSf(Delay)} \times \text{NSalesEff} = \text{Workforce} \times \text{PDY} \]

\[ \Leftrightarrow \text{SalesPeople} \times \text{NSalesEff} \times \text{EDoSf} \left( \frac{1}{\text{RelativeFinishingTime}} \right) = \text{Workforce} \times \text{PDY} \]
\[ \text{SalesPeople} \times \text{NSalesEff} \times \text{EDOSf} \left( \frac{\text{AvgFinishTime}}{\text{TargetPrDur}} \right) = \text{Workforce} \times \text{PDY} \]

\[ \text{SalesPeople} \times \text{NSalesEff} \times \text{EDOSf} \left( \frac{\text{Projects/FinishPrj}}{\text{TargetPrDur}} \right) = \text{Workforce} \times \text{PDY} \]

\[ \text{EDOSf} \left( \frac{\text{Projects}}{\text{TargetPrDur} \times \text{Workforce} \times \text{PDY}} \right) = \frac{\text{Workforce} \times \text{PDY}}{\text{SalesPeople} \times \text{NSalesEff}} \]

\[ \text{Projects} = \text{TargetPrDur} \times \text{Workforce} \times \text{PDY} \times \text{EDOSf}^{-1} \left( \frac{\text{Workforce} \times \text{PDY}}{\text{SalesPeople} \times \text{NSalesEff}} \right) \] (3.1)

Now, the equilibrium condition on the workforce is given by:

\[ \text{HiringFiring} = 0 \]

\[ \Rightarrow \text{Workforce} = \text{IndicWf} \]

\[ \Rightarrow \text{Workforce} = \min(\text{NeededWf}, \text{AffordWf}) \]

\[ \Rightarrow \text{Workforce} = \min \left( \frac{\text{Projects}}{\text{PDY} \times \text{TargetPrDur} \times \text{EmpCost}} \right) \]

\[ \Rightarrow \text{Workforce} = \min \left( \frac{\text{Projects}}{\text{PDY} \times \text{TargetPrDur} \times \text{ExpRevenues} \times \text{FrRevBgt}} \right) \]

\[ \Rightarrow \text{Workforce} = \min \left( \frac{\text{Projects}}{\text{PDY} \times \text{TargetPrDur} \times \text{PcvdRevenues} \times \text{FrRevBgt} \times (1 + \text{Trend} \times (\text{TTPcvRev} + \text{FctHzn}))} \right) \]

\[ \Rightarrow \text{Workforce} = \min \left( \frac{\text{Projects}}{\text{PDY} \times \text{TargetPrDur} \times \text{PcvdRevenues} \times \text{FrRevBgt} \times \left( 1 + \left( \frac{\text{PcvdRevenues} - \text{HistRev}}{\text{HistRev} \times \text{DurCalcTrend}} \right) \right)} \right) \] (3.2)

For the Historical Revenues, the equilibrium condition will be given by:

\[ \text{ChgHistRev} = 0 \]

\[ \Rightarrow \text{HistRev} = \text{PcvdRevenues} \] (3.3)

Finally, the equilibrium for the Perceived Revenues is given by:

\[ \text{PcvdRevenues} = \text{Revenues} \]

\[ \Rightarrow \text{PcvdRevenues} = \text{RevFinish} + \text{RevUpfront} \]

\[ \Rightarrow \text{PcvdRevenues} = \text{AvgPPrice} \times (1 - \text{FracUF}) \times \text{FinishPrj} + \text{FracUF} \times \text{SellPrj} \]

\[ \Rightarrow \text{PcvdRevenues} = \text{AvgPPrice} \times (1 - \text{FracUF}) \times \text{FinishPrj} + \text{FracUF} \times \text{SellPrj} \]
From our first condition, we know that Finishing projects equals Selling projects in equilibrium, therefore:

\[ P_{cvdRevenues} = AvgPPrice \times (1 - FracUF) \times FinishPrj + FracUF \times FinishPrj \]

\[ \Rightarrow P_{cvdRevenues} = AvgPPrice \times FinishPrj \]

\[ \Rightarrow P_{cvdRevenues} = AvgPPrice \times Workforce \times PDY \]  \hspace{1cm} (3.4)

Let's replace (3.3) into equation (3.2):

\[ Workforce = \min \left( \frac{Projects \times P_{cvdRevenues} \times FrRevBgt}{PDY \times TargetPrDur \times EmpCost} \times \left( 1 + \frac{(P_{cvdRevenues} - P_{cvdRevenues}) \times (TP_{cvdRev} + FcostHtn)}{P_{cvdRevenues} \times DurCalcTrend} \right) \right) \]

\[ \Rightarrow Workforce = \min \left( \frac{Projects \times P_{cvdRevenues} \times FrRevBgt}{PDY \times TargetPrDur \times EmpCost} \right) \]

Using equation 3.4 here, we get:

\[ \Rightarrow Workforce = \min \left( \frac{Projects \times AvgPPrice \times FrRevBgt \times Workforce \times PDY}{PDY \times TargetPrDur \times EmpCost \times FrRevBgt} \right) \]

Therefore, for non-trivial equilibrium (i.e. non-zero Workforce), we have that:

\[ Workforce = \frac{Projects}{PDY \times TargetPrDur} \]  \hspace{1cm} (3.5)

and

\[ Workforce \leq \frac{AvgPPrice \times Workforce \times PDY}{EmpCost \times FrRevBgt} \]

\[ \Rightarrow EmpCost \leq \frac{AvgPPrice \times FrRevBgt \times PDY}{EmpCost \times FrRevBgt} \]  \hspace{1cm} (3.6)

We can think of equations (3.5) and (3.6) as being the equilibrium in work and budget, respectively. The former says that in order to finish the Projects we have in the targeted amount of time, the company has to get a workforce with a certain number of people and productivity. If, for instance, the company sells a new project, it will have to increase the workforce (or perhaps the productivity) for the Target Project Duration to be met. On the other hand, equation 3.6 is showing that the selling
price of a project has to be high enough to cover the cost of the workforce needed to perform that project.

Replacing (3.5) into (3.1), we get:

$$Projects = \frac{TargetPrDur \cdot Projects}{PDY \cdot TargetPrDur} \cdot PDY \cdot EDOSf^{-1} \left( \frac{Workforce \cdot PDY}{SalesPeople \cdot NSalesEff} \right)$$

$$\Rightarrow 1 = EDOSf^{-1} \left( \frac{Workforce \cdot PDY}{SalesPeople \cdot NSalesEff} \right)$$

$$\Rightarrow Workforce = \frac{SalesPeople \cdot NSalesEff \cdot EDOSf(1)}{PDY} \quad (3.7)$$

This equation is telling us that in order to achieve equilibrium, the company needs to have enough people to work in the projects that the salespeople are selling. While possibly intuitive, there is a surprising fact in this equation. Its outcome does not depend on the effect of finishing early or late on sales, but just on the effect of finishing projects exactly on time. This means that in the equilibrium state projects are neither early nor late. In reality, the company is far from not having delays. If no equilibrium is achievable without delivery delay, and the company has a considerable delivery delay, one may think that the system is not in equilibrium.

Using the result (3.7) in (3.5), we get:

$$\frac{Projects}{PDY \cdot TargetPrDur} = \frac{SalesPeople \cdot NSalesEff \cdot EDOSf(1)}{PDY}$$

$$\Rightarrow Projects = SalesPeople \cdot NSalesEff \cdot EDOSf(1) \cdot TargetPrDur \quad (3.8)$$

This equation states a very interesting fact. In order for the system to be in equilibrium, the rate of selling projects must be equal to the ratio between the number of projects outstanding and the target time to complete the projects. The number of projects that the company can handle in the equilibrium is attached solely to market variables, and an increment in productivity, for instance, will have no effect on it.

Replacing (3.7) into (3.4), we have:

26
\[ P_{cvd\text{Revenues}} = \frac{AvgP\text{Price} \times Sales\text{People} \times NSales\text{Eff} \times EDOSf(1) \times PDY}{PDY} \]

\[ \Rightarrow P_{cvd\text{Revenues}} = AvgP\text{Price} \times Sales\text{People} \times NSales\text{Eff} \times EDOSf(1) \quad (3.9) \]

This is not surprising. In equilibrium, the perception of the revenues should be equal to the actual revenues, and, in fact, that is the initial value that the extrapolation molecule provides by default.

In order to start the system in equilibrium we added the following equations for initial conditions, shown schematically in figure 3.8.

<table>
<thead>
<tr>
<th>Initial Condition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Projects=</td>
<td>project</td>
</tr>
<tr>
<td>Sales people<em>Normal sales effectiveness</em>Effect of Delay on Sales Effectiveness f(1)*Target project duration</td>
<td></td>
</tr>
<tr>
<td>Initial Workforce=</td>
<td>person</td>
</tr>
<tr>
<td>Sales people<em>Normal sales effectiveness</em>Effect of Delay on Sales Effectiveness f(1)/PDY</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 3.8: Initial conditions for equilibrium](image-url)
Step response simulation

Now that we have the model, we would like to know what behaviors it capable of showing. Ideally, we would like to see if the company fears and hopes are among those behaviors. If so, we would like to understand what structure or parameters drive the behavior and could be used to make the hoped for outcome more likely than the feared one.

In order to study the dynamic behavior of the system, we ran a simulation starting from equilibrium and introducing a 10% step increase in Normal sales effectiveness in year 1. Since this will increase the workload, we expect to see a delay in finishing projects. The company will perceive the shortage in workforce and will start to hire, until the workforce is able to complete projects on time, and return to the equilibrium.

Figure 3.9 shows the graphic trend for Projects and Workforce. The system is stable and both, projects and workforce move smoothly to the new Equilibrium State. This is not exactly what we expected. We thought there may be some oscillations, as one might overshoot in hiring.

Figure 3.9: Step response of workforce and projects
The response is the same, even for very large changes in sales effectiveness (we tried with steps of up to 5000% the normal value). The system goes back into equilibrium in roughly 2 years. This is because the hiring can respond to the workload without limitations, since there is a stream of fresh resources from the sales increase. Notice that part of these resources (30% originally) are received "up-front", which enables the company to hire as many people as necessary. It is interesting to note that even when the projects are paid for only at completion, the overall behavior of the system remains the same. However, in this case there is a longer delay to come to equilibrium since the hiring now has to wait for the first "batch" of projects to come out the pipeline.

Going back to the reference modes previously presented, this behavior directly relates to the hopes of the company that sales may continue growing without any capacity limitations.

The delay evolution is shown in figure 3.10. The step effect on the delay is small (about 3%), and it returns fast to 1.0 (no delay). It appears that something in the model structure drives towards not finishing the projects before or after promised time. This is certainly surprising. One might expect that, since hiring is not instantaneous (Time to hire/fire is about 2.5 months), an increase in the sales
effectiveness would produce larger delays in finishing the larger amount of work with the same workforce. However, this does not significantly affect the behavior of the system, and it seems, again, that the company hopes of reducing the delay, even with growing sales, is likely to happen.

One concern arises here. We know that such a small delay is not seen in reality. This may suggest that we have not captured the entire relevant structure in this first model. However, it is worthwhile to note that there are conditions, that are captured in this model, under which it is possible for the company to maintain a low impact of a sales increment on project delays. Those conditions can be understood as a prompt reaction to sales change, as we have seen in the simulations.

Sensitivity Analysis

In order to study the effects of the different parameters in the model, we are going to run multiple simulations, varying one parameter at a time and comparing the response of Projects, Workforce, and the Delivery Delay.

Average Project Price

Figure 4.3 shows the effect of doubling and halving the Average project price. It is interesting to see that a raise in the average price to $200,000 does not change any of the variables analyzed. However, if project price drops to $50,000, the workforce falls near zero, the delay increases over any reasonable limit and the number of projects initially drops, but then begins to grow rapidly.

What is happening?

Remember that the indicated workforce is the minimum between the needed workforce and the one allowed by the budget. In our previous analysis, we assumed that the needed workforce was always less than or equal to the allowed, but this does not hold when we get half of the revenues per project. This causes workforce to decrease, which, in turn, raises delay, and decreases sales of new projects.

The reason that projects begin to increase is that we are still able to sell some, but the workforce is not able to finish them, so the stock of projects keeps growing over time (Figure 4.4).
We can think of the system as having two very different modes of behavior. One is very stable around the equilibrium, where the needed workforce is less than the affordable one and there is no delivery delay. The other is the one we just saw, where the affordable workforce is less than the needed and the delay grows out of proportion.

Recalling our equilibrium calculations, equation (3.6) provides a condition for being in equilibrium mode. The cost per employee divided by the average productivity has to be less than or equal to the average project price times the fraction of revenues to budget. If this inequality does not hold, the system will go into the budget-constrained mode.

![Figure 4.1: Average project price sensitivity analysis](image)

How can we know what mode is the company is currently in? A close tracking of projects backlog could be used to determine this. If the project backlog is increasing over a period, this should alert the company that budget-constrained mode is in place. Today, however, this tracking is not being done. Projects are monitored in a one on one basis, and no global statistics are held.

Another issue the company may want to observe is if the budget plays a role in the hiring policy. In equilibrium, budget does not impact the hiring decision, as it is always driven by the workload. If the
The company is concerned about not having enough people because of budget constraints, that is a strong indicator that the second mode is in place, making the company’s feared reference mode more likely.

---

<table>
<thead>
<tr>
<th>Mode</th>
<th>Indicated Workforce</th>
<th>Affordable Workforce</th>
<th>Needed Workforce</th>
</tr>
</thead>
<tbody>
<tr>
<td>base</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>double</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>half</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graph of Indicated Workforce, Affordable Workforce, and Needed Workforce over time.](image)

**Figure 4.2: Causal tracing for average-project-price sensitivity analysis**

---

**Duration over which to calculate trend**

As shown in Figure 4.5, doubling or halving this parameter does not affect the behavior at all. This is explained by the fact that the extrapolation piece of the model is not affecting the behavior of the systems, while in normal mode: i.e. needed workforce is less than allowed workforce.
It is interesting to see what the effect of this parameter is when the system is in budget restricted mode, which, as we just saw, can be caused by lowering the average project price. We saw that the
parameter has a strong effect on the speed at which projects and workforce drop in figure 4.6. The reason for this is that if the company has a shorter memory, the bad times have a stronger effect on the sales forecast, which reduce the budget faster, and thus the workforce is shrunk quickly.

**Employee cost**

As one may expect, the employee cost has exactly the opposite effect than the average project price. It does not matter, as long as it does not drive the affordable workforce to a lower value than the needed one (see figure 4.7).

![Employee cost sensitivity analysis](image)

**Figure 4.5: Employee cost sensitivity analysis**

**Forecast Horizon**

Again, this parameter does not have any effect in the system behavior (Figure 4.8). The rational here is analogous to the one for Duration over which to calculate trend, and we expect that it would be the same for all the extrapolating molecule parameters.
Fraction of Revenues to Budget

Doubling this variable has no effect, while halving it will cause the system to go into the budget-constrained mode that we have seen before, as shown in figure 4.9.

Up to now, we can classify the parameters we studied in two groups:

Group I: The parameter has no impact in the system behavior.

Group II: Changing the parameter in one direction has no effect in the system behavior, whereas changing in the opposite direction will cause the system to switch to the budget-constraint mode.

Fraction of revenues up-front

This parameter does not have any effect on the system behavior, as shown in figure 4.10. It is, therefore, a Group I parameter.
Figure 4.7: Fraction of revenues to budget sensitivity analysis

Figure 4.8: Fraction of revenues upfront sensitivity analysis
Productivity

PDY behaves similar to Group II parameters, in the sense that halving it switches the system to the budget-constraint mode. However, doubling PDY will have an impact in the Workforce, as seen in figure 4.11, and this is different from the other Group II parameters.

The effect is very simple and clean. Doubling PDY halves the workforce, and this makes sense since the workforce is driven by the need of it to finish the existing projects.

It is interesting to note that the projects stock is not affected by doubling the productivity. This is because the workforce is being adjusted to the new PDY so that the projects are finished just in time (not before, and not after Target project duration).

![Productivity sensitivity analysis](image)

The company might be interested in improving productivity as a way to reduce the workforce (and, hence, the costs). Laying people off is costly, but if sales are growing, the company might decide to invest in increasing productivity, instead of the workforce.
Note that a productivity increase could also take the company from budget-constrained mode into normal mode.

Increasing productivity seems to be an important factor for improvement in the company's development process. The problem is that in our model, productivity is a given parameter that we assume to be constant, so there is no insight on how to change it that we can learn from. This suggests that our next step in enhancing the model should be focused on productivity.

**Sales People**

Looking at figure 4.12, it is obvious that Sales People is not a Group I nor a Group II parameter. It does impact the system behavior when halving it and when doubling it, as well. It has a linear impact on both, workforce and projects and it does not affect Delivery Delay at all.

Why is delivery delay not being affected?

Because we have twice the number of projects, but also the workforce has been doubled, and hence the finishing-projects rate will be doubled as well. Doubling both, the number of projects and the finishing rate yields the same delivery delay.

The fact that the workforce is instantaneously doubled may surprise some readers, but it has a very simple explanation. Remember we are adjusting the initial conditions of the stocks in order to start the system in equilibrium? Well, from equation (4.7) we can see that the equilibrium value for the workforce is proportional to the number of sales people. If we double the sales force parameter, the starting workforce will, therefore, be doubled as well.

It is interesting to notice that we do not get into the budget-constraint mode in this case, since the increase in sales is increasing the budget and, therefore, the allowable workforce.
Target project duration

This parameter does not fit into groups I or II either. It has an effect on hiring. If projects are supposed to last longer, hiring is smoother. Otherwise, it is more accelerated, as shown in figure 4.13. The Delivery Delay peak is also accentuated as the Target project duration is reduced.

The surprising fact here is that the workforce is seeking the same goal of 8.25 person, no matter how fast we would like the project to be finished. The intuition says that the faster we want to finish the projects, the more people we need. However, if we recall the equilibrium calculations, equation (3.7) shows that steady state workforce does not depend on the target project duration.
Figure 4.11: Target project duration sensitivity analysis

Figure 4.12: Time to Hire and Fire sensitivity analysis
Time to Hire/Fire

This parameter has a strong effect on the Delivery Delay, as seen in figure 4.14. The larger the TT Fire/Hire, the slower the workforce will adjust to the new conditions.

Time to Perceive Delay

The effect of changing TT Perceive Delay is shown in figure 4.15. This parameter indicates how long it takes the market to realize the company's delivery delay. As we increase this time, projects and workforce will show small oscillations that will damp quickly.

![Figure 4.13: Time to Hire and Fire sensitivity analysis](image)

Time to Perceive Revenues

TT Perceive Revenues belongs to Group I. Varying this parameter does not affect system behavior, as shown in figure 4.16.
Three Modes of Behavior

The sensitivity analysis is showing that there is a large part of the model that is not affecting the dynamics when the system is in normal mode. One question one might ask is whether the normal-mode is the mode that we see in the real world. It does not seem so.

It is counter-intuitive that the R&D budget is always much larger than needed. This is what maintains the system in the normal-mode. This suggests that the parameter election may not be adequate. It seems reasonable that budget allocation should be close to what is needed when in the equilibrium state, so we may want to recalculate some parameters, such as fraction of sales to budget.

From equation (4.6), we had that in order to have non-trivial equilibrium, the following inequality should hold:

\[ FrRevBgt \leq \frac{EmpCost}{AvgPPrice*PDY} \]
Thus, to address the R&D budget over-allocation, we can change the above inequality into its equality form. With this, the fraction of the revenues from selling a project that go to R&D are exactly what is needed to finish that project.

In our case,

\[
FrRevBgt = \frac{EmpCost}{AvgPPrice \times PDY} = \frac{50,000 \text{$/Year/person}}{100,000 \text{$/project} \times 4 \text{project/person/Year}} = 0.125
\]

By doing this, we obtained a quite interesting behavior. Figure 4.17 illustrates the evolution of projects for a 10% step increase in sales effectiveness.

**Figure 4.15: Borderline mode step response for projects**
We see that projects have an overshoot in this case, with a small oscillation that is damped after year 9, but the behavior looks similar to the base simulation, where we had a Fraction of Revenues to Budget of 2.

A very different situation is the one we see with the workforce (figure 4.18), which climbs in a much slower manner than in our base case. It seems that the budget is constraining the hiring rate, so the workforce takes about 8 years to get to the needed level, instead of the 3 years for the base case.

This is shown in figure 4.19. The indicated workforce is the minimum between the needed and the affordable workforce. The affordable workforce does not grow fast enough. This, in turn, is caused by a drop in revenues that shows the effect of a strong depression on selling projects. The latter is caused by a drop in sales effectiveness, which is explained by an increase in delivery delay, as seen in figure 4.20.

![Graph for Workforce](image)

**Graph for Workforce**

<table>
<thead>
<tr>
<th>Time (Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>7</td>
</tr>
</tbody>
</table>

Workforce: Borderline ___________________________ person
Workforce: Normal _______________________________ person

Figure 4.16: Borderline mode step response for workforce
We can see that this behavior is very different from the two modes (normal and constrained) we found before. This leads us to three possible modes of behavior for the system, as seen in figures 4.19, 4.20, and 4.21.

In the Normal mode, workforce increases quickly after the sales increase, so the working capacity (project finishing) aligns promptly with the sales rate, which has a very small drop and returns to its equilibrium value after 2 years. This would support the company’s hope, as long as the sales drop remains small.
Figure 4.18: Causal trace in borderline mode
finishing projects: Normal \[\text{project/Year}\]
Selling Projects: Normal \[\text{project/Year}\]

Figure 4.19: Selling and finishing projects in Normal mode

finishing projects: Constrained \[\text{project/Year}\]
Selling Projects: Constrained \[\text{project/Year}\]

Figure 4.20: Selling and finishing projects in Constrained mode
The **Constraint** mode, on the other hand, is aligned with company's fear. The sales cannot support the workforce so the workforce cannot support the project load, and this leads into even fewer sales. With no equilibrium point except for the trivial one, the company is driven into bankruptcy.

In the **Borderline** mode, the workforce will not increase fast enough to support the additional sales. As delivery delay increases, sales will drop significantly. Since hiring was in place, the workforce is now able to finish the projects in time, and the sales will grow up to the new equilibrium point. This, however, will take about 7 years, with very discouraging results in the first 2 years.
Eigenvalue Analysis

In this chapter, we are going to develop an Eigenvalue analysis of our model. This analysis will provide us a better understanding of all the different behaviors we could see in our model, as well as how are they linked to particular loops.

To do the analysis, we will linearize the system's equations at a point in time of interest. By doing that, we will be able to express the model as:

\[
\frac{\partial x}{\partial t} = Ax + b
\]

With \( x \) being our state vector, composed by all the levels:

\[
x = \begin{bmatrix}
\text{PerceivedDeliveryDelay} \\
\text{PerceivedRevenues} \\
\text{HistoricalRevenues} \\
\text{Projects} \\
\text{Workforce}
\end{bmatrix}
\]

The dynamic matrix \( A \), and in particular its eigenvalues, determine the behavior of the system. By definition, if we find a scalar \( \lambda \) and a vector \( x \) that satisfy the equation \( A \cdot x = \lambda \cdot x \), then \( \lambda \) is an eigenvalue of the matrix \( A \), and \( x \) is its associated eigenvector.

The different behavior modes of a linear dynamic system will be driven by the eigenvalues of the dynamic matrix. The real part of the eigenvalue will determine the mode stability. A negative real part will cause decay or goal seeking modes, whereas a positive eigenvalue will cause exponential growth (positive or negative). In all cases, the associated time constant will be the inverse of the eigenvalue's real part.

A pure imaginary eigenvalue will cause never-damping oscillations with the period equal to \( 2\pi \) divided by the eigenvalue. A complex eigenvalue will cause oscillations and either growth or decay, depending
on the sign of its real part. The Time constant is determined by the real part while the imaginary part determines the frequency of oscillation. This is shown graphically in figure 5.1. Note that complex eigenvalues always come in conjugate pairs of the form \( \alpha \pm j\beta \), where \( j = \sqrt{-1} \). Therefore, the polarity of the imaginary part is not relevant.

![Diagram of eigenvalue analysis](image)

**Figure 5.1:** Behavioral modes as a function of the eigenvalue real and imaginary parts.

**Eigenvalue analysis for Normal mode**

The first step for the eigenvalue analysis is to obtain the dynamic matrix that represents the behavior of our system at a given instant. In the simulations (see figure 5.2), it seems that \( t=1.5 \) is representative of the behavior we are interested in.

Where can we get the dynamic matrix? Actually, the dynamic simulator we are using (Ventana's Vensim™) creates a discrete dynamic matrix by linearizing the differential equations at every time step. We can obtain this matrix from Vensim's error log file. In our case it looks as follows:
Using Analyzit™ [Hines, 1999d], we obtained the following eigenvalues for this matrix:

\[
\begin{pmatrix}
-2 & 0 & 0 & 0.127 & -0.256 \\
-989,920 & -1 & 0 & 0 & 280,000 \\
0 & 0 & 0.333 & -0.332 & 0 \\
-33 & 0 & 0 & 0 & -4 \\
0 & 0 & 0 & 2.499 & -5
\end{pmatrix}
\]

\[
A =
\]

\[
\lambda_1 = -0.332 \text{[year}^{-1}] = \frac{-1}{3.004 \text{[year]}} = \frac{-1}{\tau_1}
\]

\[
\lambda_2 = -1.16 \text{[year}^{-1}] = \frac{-1}{0.862 \text{[year]}} = \frac{-1}{\tau_2}
\]

\[
\lambda_3 = -1 \text{[year}^{-1}] = \frac{-1}{1 \text{[year]}} = \frac{-1}{\tau_3}
\]

\[
\lambda_4 = -2.937 \text{[year}^{-1}] - 2.957 \text{[rad/yr]} = \frac{-1}{0.340 \text{[year]}} + \frac{2\pi}{2.125 \text{[year]}} j = \frac{-1}{\tau_4} + j \frac{2\pi}{\tau_4}
\]

\[
\lambda_5 = -2.937 \text{[year}^{-1}] - 2.957 \text{[rad/yr]} = \frac{-1}{0.340 \text{[year]}} - \frac{2\pi}{2.125 \text{[year]}} j = \frac{-1}{\tau_4} - j \frac{2\pi}{\tau_4}
\]

The goal-seeking behavior that we see in workforce and projects is associated to real negative eigenvalues. As figure 5.2 shows, the new equilibrium is reached in about 3 years, which is consistent with the value of \(\lambda_2\), but also with \(\lambda_3\).
How could we know which is the eigenvalue behind the behavior of workforce and projects?

In order to answer this question, let us take a look at the sensitivity of the eigenvalues to the inter-level strengths.

In the case of $\lambda_3$, the most significant contributors to the eigenvalue are:

<table>
<thead>
<tr>
<th>Link</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>HisRev$\rightarrow$HisRev</td>
<td>-11.805461918781434</td>
</tr>
<tr>
<td>Workforce$\rightarrow$Projects</td>
<td>-11.800393327174433</td>
</tr>
<tr>
<td>Projects$\rightarrow$Workforce</td>
<td>-11.797545717348537</td>
</tr>
<tr>
<td>Workforce$\rightarrow$PDelay</td>
<td>-1.535505110582716</td>
</tr>
<tr>
<td>Projects$\rightarrow$PDelay</td>
<td>1.1750991279418974</td>
</tr>
<tr>
<td>Workforce$\rightarrow$Workforce</td>
<td>1.1657746761679766</td>
</tr>
<tr>
<td>PDelay$\rightarrow$PDelay</td>
<td>0.8154505774593064</td>
</tr>
<tr>
<td>PDelay$\rightarrow$Projects</td>
<td>-0.3507335731557295</td>
</tr>
</tbody>
</table>

This indicates that the loops that influence this eigenvalue the most are the Historical Revenues to itself, and the Projects to Workforce to Projects. These loops are highlighted in figure 5.3.

If we make the same analysis on $\lambda_3$, we get the following result:

<table>
<thead>
<tr>
<th>Link</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workforce$\rightarrow$Projects</td>
<td>12.429545586187244</td>
</tr>
<tr>
<td>HisRev$\rightarrow$HisRev</td>
<td>11.805366209286644</td>
</tr>
<tr>
<td>Projects$\rightarrow$Workforce</td>
<td>10.907237858761755</td>
</tr>
<tr>
<td>PRev$\rightarrow$Prev</td>
<td>0.9876358606706576</td>
</tr>
<tr>
<td>PDelay$\rightarrow$Projects</td>
<td>-0.0071234040355804</td>
</tr>
<tr>
<td>PRev$\rightarrow$HisRev</td>
<td>-0.006510136872368225</td>
</tr>
<tr>
<td>PDelay$\rightarrow$PRev</td>
<td>0.006244091734371165</td>
</tr>
<tr>
<td>Workforce$\rightarrow$Workforce</td>
<td>-0.0049479149516273215</td>
</tr>
<tr>
<td>Projects$\rightarrow$PDelay</td>
<td>-0.004377675677434631</td>
</tr>
<tr>
<td>Workforce$\rightarrow$PDelay</td>
<td>-3.134678071873736E-4</td>
</tr>
<tr>
<td>PDelay$\rightarrow$PDelay</td>
<td>6.439316154667695E-4</td>
</tr>
<tr>
<td>Workforce$\rightarrow$PRev</td>
<td>-3.134678071873736E-4</td>
</tr>
</tbody>
</table>
The links are highlighted in the schematic of figure 5.4. Here, the dominant loops are the Historical Revenues to itself, the Projects to Workforce to Projects loop, and the Perceived Revenues to itself.

This last stock is unlikely to affect the workforce and projects behavior in normal mode, since the budget is well over the needed and, therefore, the forecast is not used to determine hiring.

This would suggest that the behavior we are observing for Workforce and Projects is driven by $\lambda_2$, rather than $\lambda_3$.

What about the oscillatory behavior suggested by the complex conjugate eigenvalue pair $\lambda_3$ and $\lambda_3$? We see no oscillation in Workforce or Projects. However, if we look at the selling projects rate for Normal mode (figure 4.19), there is an oscillation during the first year. This is consistent with the real part of $\lambda_4$ ($3^*\tau_4 \approx 1.02$ year).
This oscillation in sales is not something the company would like to have, so let us take a look at the links that affect both the real and the imaginary part of $\lambda_i$:

<table>
<thead>
<tr>
<th>Link</th>
<th>$1/\tau_i$ sensitivity</th>
<th>$T_i$ sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workforce $\rightarrow$ Workforce</td>
<td>0.6255047799929336</td>
<td>0.72007269223105</td>
</tr>
<tr>
<td>Workforce $\rightarrow$ Pdelay</td>
<td>0.2922701906965066</td>
<td>-0.17525560282077207</td>
</tr>
<tr>
<td>Projects $\rightarrow$ Pdelay</td>
<td>-0.22594431081966293</td>
<td>-0.100592398563233</td>
</tr>
<tr>
<td>Pdelay $\rightarrow$ Pdelay</td>
<td>0.18349370961277442</td>
<td>-0.01081207140730382</td>
</tr>
<tr>
<td>Projects $\rightarrow$ Workforce</td>
<td>0.1703764833378355</td>
<td>-0.6569750815751557</td>
</tr>
<tr>
<td>Workforce $\rightarrow$ Projects</td>
<td>-0.12116819975945088</td>
<td>-0.485111626082909</td>
</tr>
<tr>
<td>Pdelay $\rightarrow$ Projects</td>
<td>0.06829161161762017</td>
<td>-0.27382999714184636</td>
</tr>
</tbody>
</table>

This is telling us that the Workforce to Workforce loop is the major responsible for the oscillatory mode. An increment in the loop strength will have two effects on the oscillation: It will decrease $\tau_i$, causing the oscillation to last less time and it will increase the period, reducing the oscillatory behavior.
In our model, the strength of the Workforce to Workforce loop is given by the inverse of the Time to Hire/Fire. Therefore, according to our eigenvalue analysis, reducing TT Hire/Fire should reduce the oscillations, whereas incrementing this parameter should have the opposite effect. This finding was confirmed with the simulation shown in figure 5.5.

![Figure 5.5: Effect of Time to Hire/Fire on Selling Projects in Normal mode](image)

As we have seen, even in Normal mode, the company can see that if sales have a steep increase, they are likely to experience a drop in the short term. The magnitude of this drop could be diminished significantly if the company is able to accelerate the hiring process.

**Eigenvalue analysis for Borderline mode**

Let us now switch to Borderline mode by decreasing the fraction of revenues to budget to 0.125.

From looking at figure 4.16, we see it would be interesting to analyze the behavior around t=5 years. The dynamic matrix for that time is:
The eigenvalues are:

\[ \lambda_1 = -6.052 [\text{year}^{-1}] = \frac{-1}{0.165 [\text{year}]} = \frac{-1}{\tau_1} \]
\[ \lambda_2 = -1.255 [\text{year}^{-1}] + 1.746 [\text{rad/year}] = \frac{-1}{0.797 [\text{year}]} + \frac{2\pi}{3.598 [\text{year}]} j = \frac{-1}{\tau_2} + j \frac{2\pi}{T_2} \]
\[ \lambda_3 = -1.255 [\text{year}^{-1}] - 1.746 [\text{rad/year}] = \frac{-1}{0.797 [\text{year}]} - \frac{2\pi}{3.598 [\text{year}]} j = \frac{-1}{\tau_2} - j \frac{2\pi}{T_2} \]
\[ \lambda_4 = 0.241 [\text{year}^{-1}] = \frac{1}{4.149 [\text{year}]} = \frac{1}{\tau_4} \]
\[ \lambda_5 = -0.0127 [\text{year}^{-1}] = \frac{-1}{76.92 [\text{year}]} = \frac{1}{\tau_5} \]

One surprising fact came out immediately. \( \lambda_4 \) is a real positive number. This means we have an unstable system, capable of exponential growth, but we do not see it.

The unstable mode could be hidden by two modes annulling each other, but that would produce an unstable equilibrium state, and a small deviation from the initial conditions should destabilize the system and make the growth mode explicit. We ran several simulations with different initial conditions, but the system always reached the equilibrium, so this hypothesis was proven wrong.

We know the system should show exponential growth (or decay) because there is a positive eigenvalue. The only explanation possible then is that maybe the eigenvalue gets negative after a while.

This is possible in non-linear systems. There are many sources of non-linearity in our model. The obvious ones are the lookup function for the effect of delay in sales effectiveness, and the use of the \text{min} function to compute the indicated workforce. A less obvious one is the calculation of the average finishing time:
AvgFinishTime = \frac{\text{Projects}}{\text{FinishingPrj}}

\frac{\text{Projects}}{\text{Workforce} \cdot \text{PDY}}

The quotient between two stocks adds another non-linearity to our model, as it is used as an input for another stock: the perceived delivery delay.

All these non-linearities will cause the dynamic matrix \( A \) to change over time, depending on the actual state of the system, represented by the stocks vector \( x \). A change in the matrix \( A \) would cause a change in the eigenvalues, enabling our system to become stable.

In order to find out is this is what is actually happening, let us take a look at the dynamic matrix for \( t=6 \) years:

\[
A = \begin{bmatrix}
-2 & 0 & 0 & 0.124 & -0.248 \\
-990,080 & -1 & 0 & 0 & 280,000 \\
0 & 0.333 & -0.333 & 0 & 0 \\
-32.008 & 0 & 0 & 0 & -4 \\
0 & 0.0000121 & 0.00000873 & 2.499 & -5
\end{bmatrix}
\]

As we can see, the dynamic matrix is slightly different from the one for \( t=5 \) years. This new matrix has the following eigenvalues:

\[
\lambda_1' = -5.66 \text{[year}^-1]\]
\[
\lambda_2' = -1.179 \text{[year}^-1] + 1.704 j \text{[rad/year]}
\]
\[
\lambda_3' = -1.179 \text{[year}^-1] - 1.704 j \text{[rad/year]}
\]
\[
\lambda_4' = -0.157 \text{[year}^-1] + 0.425 j \text{[rad/year]}
\]
\[
\lambda_5' = -0.157 \text{[year}^-1] - 0.425 j \text{[rad/year]}
\]
The unstable eigenvalue is gone. This little change in the dynamic matrix enables the system to reach equilibrium. Taking a look at the evolution of $\lambda_4$ and $\lambda_5$ (see figure 5.6), we see that the system goes through a growing oscillations mode. The eigenvalue pair moves quickly to the real negative semi-plane, stabilizing the system into damping oscillatory behavior.

As the growing oscillations mode lasts only for $1/16$ of a year, we are not able to notice it easily. However, we should be able to observe two very different modes of behavior in the system. The first mode should show exponential growth, whereas the second one should have some damping oscillations and goal seeking towards the equilibrium. Taking a careful look at the Borderline mode simulations (see figure 5.7), we can identify these behavioral modes.
The company would like to be able to accelerate the workforce ramp-up in order to support the increasing sales. This could be achieved by increasing $\lambda_4$ in order to have a faster exponential growth.

The sensibility of $\lambda_4$ to the different links between stocks is:

<table>
<thead>
<tr>
<th>Link</th>
<th>Sensibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRev $\rightarrow$ Workfce</td>
<td>10.086547788369769</td>
</tr>
<tr>
<td>Workfce $\rightarrow$ Workfce</td>
<td>-8.881780515975523</td>
</tr>
<tr>
<td>PRev $\rightarrow$ Prev</td>
<td>-7.489401324415392</td>
</tr>
<tr>
<td>Workfce $\rightarrow$ Prev</td>
<td>5.715678073140167</td>
</tr>
<tr>
<td>HisRev $\rightarrow$ Workfce</td>
<td>-2.7634516254874786</td>
</tr>
<tr>
<td>PRev $\rightarrow$ HisRev</td>
<td>-2.763337433689054</td>
</tr>
<tr>
<td>PDelay $\rightarrow$ Prev</td>
<td>2.5091396804878703</td>
</tr>
<tr>
<td>PDelay $\rightarrow$ Projects</td>
<td>-2.312403435660041</td>
</tr>
<tr>
<td>Workfce $\rightarrow$ Projects</td>
<td>2.2343942484078037</td>
</tr>
<tr>
<td>HisRev $\rightarrow$ HisRev</td>
<td>1.485543680043632</td>
</tr>
<tr>
<td>Workfce $\rightarrow$ Pdelay</td>
<td>0.2816253034341263</td>
</tr>
<tr>
<td>PDelay $\rightarrow$ Pdelay</td>
<td>-0.26411684280547804</td>
</tr>
<tr>
<td>Projects $\rightarrow$ Pdelay</td>
<td>0.01389286125520615</td>
</tr>
</tbody>
</table>
These strengths are shown graphically in figure 5.8. The dark gray lines represent positive sensibility and the light gray lines represent negative sensibility. The thickness. The major contributors to this mode are the Workforce to Perceived Revenues to Workforce loop, the Workforce to Workforce loop and the Perceived Revenues to Perceived Revenues loop.

We could try to affect the Workforce to Workforce loop, by changing the Time to Hire/Fire. However, this will also influence the Workforce to Perceived Revenues to Workforce loop, which has the opposite effect on $\lambda_4$.

The Forecast Horizon parameter effect on Workforce to Perceived Revenues to Workforce loop strength offers an uncoupled way to influence $\lambda_4$. An increase in the loop strength should cause a faster exponential growth, and we could achieve it by raising the Forecast Horizon. Figure 5.9 shows a simulation that explores the effect of doubling and halving the Forecast Horizon, supporting our eigenvalue analysis finding.

Figure 5.8: Links that influence $\lambda_4$ in Borderline mode
This finding enables the company to reduce the duration of the low sales period significantly. To do so, the company should increase the forecast horizon used to determine the budget. If, for instance, the company considers the revenues forecast of the next 2 years, instead of just the next year, the sales will recover faster.

An easier to implement policy with a similar effect would be to reduce the duration over which to calculate the trend. This will have a strong positive effect on $\lambda_4$, but will also have a weaker negative effect as the Historical Revenues to Historical Revenues loop strength is also affected by this parameter.
A simulation confirms that the positive effect is the dominant one. Reducing the Duration over which to calculate the trend makes sales to grow faster, after the drop, as seen in figure 5.10.

The company should, therefore build their forecasts based in a short-term trend. This will enable them to react quickly to the sales increment and be able to hire the workforce needed to support such increment.

Figure 5.10: Effect of Duration over which to calculate trend in Borderline mode
Now, let us take a look at the sales drop itself. This is caused by the oscillatory mode of \( \lambda_2 \), as shown in figure 5.7. The sensitivity of both, the real and the imaginary part of \( \lambda_2 \) to the links strength are:

<table>
<thead>
<tr>
<th>Link</th>
<th>( T_1 ) sensitivity</th>
<th>( T_2 ) sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDelay ( \rightarrow ) Pdelay</td>
<td>0.790131798022996</td>
<td>0.30658161440522197</td>
</tr>
<tr>
<td>PDelay ( \rightarrow ) Prev</td>
<td>0.1885726880390152</td>
<td>0.00750955012191353</td>
</tr>
<tr>
<td>PDelay ( \rightarrow ) Projects</td>
<td>-0.1145472958742792</td>
<td>-0.615096726825091</td>
</tr>
<tr>
<td>Workfce ( \rightarrow ) Pdelay</td>
<td>0.10514857010965471</td>
<td>0.1357055423578698</td>
</tr>
<tr>
<td>PRev ( \rightarrow ) Workfce</td>
<td>0.100848183704459</td>
<td>-0.037799435873813035</td>
</tr>
<tr>
<td>Workfce ( \rightarrow ) Workfce</td>
<td>-0.09399562520683907</td>
<td>0.07687693110098877</td>
</tr>
<tr>
<td>Workfce ( \rightarrow ) Projects</td>
<td>0.0835147519042146</td>
<td>-0.12775890898428996</td>
</tr>
<tr>
<td>Workfce ( \rightarrow ) Prev</td>
<td>-0.08068700545899897</td>
<td>-0.042008061479322276</td>
</tr>
<tr>
<td>PRev ( \rightarrow ) Prev</td>
<td>0.035781427784083636</td>
<td>0.040773423221328556</td>
</tr>
<tr>
<td>Projects ( \rightarrow ) Pdelay</td>
<td>-0.031247504669650993</td>
<td>-0.7407715707013921</td>
</tr>
<tr>
<td>PRev ( \rightarrow ) HisRev</td>
<td>0.006441127351426106</td>
<td>0.0032697291574111955</td>
</tr>
<tr>
<td>HisRev ( \rightarrow ) Workfce</td>
<td>0.00643858225592265</td>
<td>0.0032045669494421736</td>
</tr>
</tbody>
</table>

The most important contributors to the real part are the Perceived Delay to Perceived Delay loop, and the Perceived Delay to Perceived Revenues to Workforce to Perceived Delay loop.

The key influences to the imaginary part come from Projects to Perceived Delay to Projects loop, and the Perceived Delay to Perceived Delay loop. Figure 5.11 shows in dark gray those link strengths that increase the oscillatory behavior, and in light gray those which tend to damp the oscillations.
From this, we learn that the Workforce to Perceived Delivery Delay to Perceived Revenues to Workforce loop strength influences the oscillatory behavior. An increase in the strength should damp the oscillations faster.

The strength of the loop is affected by the inverse of the Time to Perceive Revenues. A decrease in this parameter should make the system less oscillatory. The simulation shown in figure 5.12 confirmed this finding.

This means that the company could reduce the sales drop by reducing the time that takes management to get the revenue information. Nowadays, this information is collected yearly. A quarterly sales report would result in a faster reaction to the sales increase, reducing the sales drop that happens immediately after the increase.
Conclusions

This thesis studied the software development business for a particular company using system dynamics modeling and analysis.

As stated in the reference modes, the company feared that an increase in project sales could produce delivery delay, and detriment future sales. They hoped to be able to overcome the problems with the policies in practice.

Dynamic hypotheses were created to show the causal relationships among important variables for the company. These hypotheses took the form of causal loops that could produce both the company's feared and hoped-for behavior.
We decided to focus on a single pair of causal loops: budget and work-to-do. As sales grow, so does the budget for hiring programmers, and hence, the delivery delay could be controlled by having a larger workforce. However, at the same time, a growth in sales would increase the work to do and result in delay, which affects future sales.

A fifth order dynamic model was build to capture this dynamic hypothesis. Computer simulations showed that the model was capable of producing the company's hope behavior.

This capability was linked to the existence of an equilibrium point in the model. If there is no non-trivial equilibrium point, the company ends in bankruptcy. In order for this equilibrium to exist, the company should be able to support the workforce needed to build a project with the fraction of the revenues from that project that go into the budget.

The simulations showed the existence of 3 modes of behavior: The normal mode, associated with the company's hope; the constrained mode, associated with bankruptcy, and the borderline mode, associated with the company's fear.

Sensitivity analysis was performed on the model to better understand how the parameters can drive the system into each of the three modes.

It turned out that while in normal mode, many parameters did not have any effect unless the variation was significant enough to drive the company into constraint mode. The parameters that can have this effect are those that determine the equilibrium point: average project price, cost per employee, productivity, and fraction of revenues to budget. If some of these parameters is about to change, the company should closely examine whether a project sale can still pay for the work needed to finish it. The company also should keep track of the project backlog, and to pay attention to the way hiring and firing is decided, in order to know when they are about to leave the normal mode.

Eigenvalue analysis was performed for normal and borderline modes to find out policies that can help sustain sales and control the delivery delay. This provided a deeper insight into the model, and also gave us the opportunity to explore the potential of this innovative approach.

We have seen that even in normal mode, a fast growth in sales is followed by a drop, caused mainly by a workforce shortage. Workforce does not grow as fast as sales, so delivery delay increases and
affects subsequent revenues. Eigenvalue elasticity analysis shows that accelerating the company's
hiring procedures can reduce the sales drop significantly, as the workforce is able to adjust faster to
the changing market conditions.

In borderline mode, the workforce growth speed is not only restricted by the hiring speed, but also by
the budget. The drop in sales that follows a fast increase is even more significant, and it lasts longer as
well. Eigenvalue analysis shows that the low-sales period duration can be reduced by considering a
shorter history when doing a sales forecast. Furthermore, the depth of the revenues drop can be
diminished by reducing the time it takes for the company's managers to get the actual sales numbers.

Eigenvalue analysis proved to be a powerful tool. We believe that there is a large potential in the use
of this kind of analysis for understanding the behaviors that a dynamic system can show.

An experienced system dynamicist could use Eigenvalue Elasticity Analysis to get deeper and faster
results than using the usual procedures of turning loops on and off for understanding complex
behaviors. In the case of the author, a practitioner with modest experience in System Dynamics,
eigenvalue analysis was valuable to gain a complete understanding of the model behavioral
capabilities.

Perhaps the main benefit of this approach would be perceived by newcomers to the field. Eigenvalue
elasticity analysis could be used to automate the explanations that link structure and behavior. This
could provide an initial source of insights to people that have no experience in model analysis.

There is still a lot of work to do in this field, in order to have a structured method to perform this
kind of analysis. An important issue to address is the fact that eigenvalues change in time, as the
system's state evolves. This makes the analysis valid only under certain conditions. Finding these
conditions – maybe in a form of confidence ranges – is one part of the problem. The other part is
finding possible behavioral modes that are not present in a single simulation, but that could be
triggered by some parameter change. This suggests that a comprehensive analysis tool might benefit
from linking eigenvalue elasticity with sensitivity analyses.

With regards to the specific software development problem of this company, even with the simple
model we developed, we were able to find some powerful levers that could help the company to make
their hope more likely than the fear.
We would have liked to explore more causal loops and to add them to our model. It seems that a constant productivity is an over-simplification for a software development problem. Next steps should consider influences on productivity, such as skill and fatigue. Without them, it would be not possible to test the actual policies that the company has in place today.

The experience of building this simple model and being able to analyze and understand it provides a solid foundation on which to build new structure that reflects additional hypotheses.
REFERENCES


Appendix A
Equations for the Dynamic Model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Affordable Workforce = Budget / Employee cost</td>
<td>person</td>
</tr>
<tr>
<td>Average finishing time = Projects / finishing projects</td>
<td>Year</td>
</tr>
<tr>
<td>Average project price = 1000000</td>
<td>$/project</td>
</tr>
<tr>
<td>Budget = Expected Revenues * Fraction of Revenues to Budget</td>
<td>$/Year</td>
</tr>
<tr>
<td>Change In Historical Revenues = (Perceived Revenues - Historical Revenues) / DurationOverWhichToCalculateTrend</td>
<td>$/(Year^2 Year)</td>
</tr>
<tr>
<td>Delivery Delay = 1 / Relative finishing time</td>
<td>fraction</td>
</tr>
<tr>
<td>DurationOverWhichToCalculateTrend = 3</td>
<td>years</td>
</tr>
<tr>
<td>Effect of Delay on Sales Effectiveness f ([0,0] - (4,2), (0,0), (1,5), (0,1.5), (1,1), (1,5,0.5), (2,0.1), (3,0.1))</td>
<td>fraction</td>
</tr>
<tr>
<td>Employee cost = 50000</td>
<td>$/(person*Year)</td>
</tr>
<tr>
<td>Expected Revenues = Perceived Revenues * (1 + FractionalTrend * (TT Perceive Revenues + ForecastHorizon))</td>
<td>$/Year</td>
</tr>
<tr>
<td>FINAL TIME = 20</td>
<td>Year</td>
</tr>
<tr>
<td>finishing projects = Workforce * PDY</td>
<td>project/Year</td>
</tr>
<tr>
<td>ForecastHorizon = 1</td>
<td>Year</td>
</tr>
<tr>
<td>Fraction of Revenues to Budget = 0.2</td>
<td>fraction</td>
</tr>
<tr>
<td>fraction of revenues upfront = 0.3</td>
<td>fraction</td>
</tr>
<tr>
<td>FractionalTrend = (Perceived Revenues - Historical Revenues) / (Historical Revenues * DurationOverWhichToCalculateTrend)</td>
<td>fraction/Year</td>
</tr>
<tr>
<td>HiringFiring = (Indicated Workforce - Workforce) / TT</td>
<td>person/Year</td>
</tr>
<tr>
<td>Historical Revenues = INTEG(Change In Historical Revenues, Perceived Revenues)</td>
<td>$/Year</td>
</tr>
<tr>
<td>Indicated Workforce = min(Needed Workforce, Affordable Workforce)</td>
<td>person</td>
</tr>
<tr>
<td>Initial Projects = Sales people * Normal sales effectiveness * Effect of Delay on Sales Effectiveness f (1) * Target project duration</td>
<td>project</td>
</tr>
<tr>
<td>INITIAL TIME = 0</td>
<td>Year</td>
</tr>
<tr>
<td>Initial Workforce = Sales people * Normal sales effectiveness * Effect of Delay on Sales Effectiveness f (1) / PDY</td>
<td>person</td>
</tr>
<tr>
<td>Needed Workforce = Projects / PDY / Target project duration</td>
<td>person</td>
</tr>
<tr>
<td>Normal sales effectiveness = 5 * (1 + STEP (0.1, 1))</td>
<td>project/(person*Year)</td>
</tr>
<tr>
<td>PDY = 4</td>
<td>project/Year</td>
</tr>
<tr>
<td>Perceived Delivery Delay = SMOOTH (Delivery Delay, TT Perceive Delay)</td>
<td>fraction</td>
</tr>
<tr>
<td>Perceived Revenues = SMOOTH (Revenues, TT Perceive Revenues)</td>
<td>$/Year</td>
</tr>
<tr>
<td>Formula</td>
<td>Unit</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Projects = INTEG(Selling Projects - finishing projects, Initial Projects)</td>
<td>project</td>
</tr>
<tr>
<td>Relative finishing time = Target project duration / Average finishing time</td>
<td>fraction</td>
</tr>
<tr>
<td>Revenues = Revenues from finishing + Revenues upfront $/Year</td>
<td>$/Year</td>
</tr>
<tr>
<td>Revenues from finishing = Average project price * finishing projects * (1 - fraction of revenues upfront) $/Year</td>
<td>$/Year</td>
</tr>
<tr>
<td>Revenues upfront = Selling Projects * Average project price * fraction of revenues upfront $/Year</td>
<td>$/Year</td>
</tr>
<tr>
<td>Sales effectiveness = Effect of Delay on Sales Effectiveness f (Perceived Delivery Delay) * Normal sales effectiveness</td>
<td>project/(person*Year)</td>
</tr>
<tr>
<td>Sales people = 6 person</td>
<td>person</td>
</tr>
<tr>
<td>SAVEPER = TIME STEP Year</td>
<td>Year</td>
</tr>
<tr>
<td>Selling Projects = Sales people * Sales effectiveness project/Year</td>
<td>project/Year</td>
</tr>
<tr>
<td>Target project duration = 0.5 Year</td>
<td>Year</td>
</tr>
<tr>
<td>TIME STEP = 0.0625 Year</td>
<td>Year</td>
</tr>
<tr>
<td>TT HireFire = 0.2 Year</td>
<td>Year</td>
</tr>
<tr>
<td>TT Perceive Delay = 0.5 Year</td>
<td>Year</td>
</tr>
<tr>
<td>TT Perceive Revenues = 1 Year</td>
<td>Year</td>
</tr>
<tr>
<td>Workforce = INTEG(HiringFiring, Initial Workforce) person</td>
<td>person</td>
</tr>
</tbody>
</table>