System Dynamics Analysis of the Growth and Management of a Graduate Robotics Lab

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ABSTRACT

In November of 2012, a robotics research laboratory at a southeastern university began to work on a multi-million dollar robotics project to participate in a national level robotics competition. This project was led by a robotics lab referred to as the Southeastern Robotics Lab (SRL) in this report, and included three additional partners from other research centers, corporations, and universities (referred as Partner A, Partner B and Partner C). While SRL is an experienced robotics laboratory which had performed successfully on various large scale robotics projects, the new project was managerially much more complex due to the involvement of several external organizations, the size of the project, availability of financial resources, and the strictness of the deadlines. The project failed to meet its desired outcome with the project team unable to field a completed system as intended at the end of the scope of work (13 months from project start to conclusion). The failure was an example of common shortcomings in multi-organizational innovative projects. Using the SRL case, we offer a simulation-supported explanation for why complex high-tech projects frequently fail. We gather data through interviewing several researchers directly involved in the project, and conduct textual analysis of archival data through the project. Then we build a system dynamics model of the system and conduct simulation-based analysis of the case. The study offers managerial implications for similar large scale projects.

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1. Introduction

In November of 2012, a robotics research laboratory at a southeastern university began work on a multi-million dollar robotics project to participate in a national level robotics competition. This project was led by a robotics lab referred to as the Southeastern Robotics Lab (SRL) in this report, and included three additional partners from other research centers, corporations, and universities (referred as Partner A, Partner B and Partner C). The four organizations were geographically separated at both foreign and domestic locations.

SRL is an experienced robotics laboratory which had performed successfully on various large scale robotics projects, in the past. The lab had for several years been growing both in the number of graduate students it funded but also the complexity of the projects it worked on having very successfully competed in a previous national level robotics program. Despite this past success, the new project was managerially much more complex due to the involvement of several external organizations, the size of the project, availability of financial resources, and the strictness of the deadlines.

The project failed to meet its desired outcome, with the project team unable to field a completed system as intended at the end of the scope of work (13 months from project start to conclusion). Since the conclusion of the project in December 2013, the fundamental technologies have continued to develop and have been ruled out as the primary source of project failure. Additionally SRL, as well as Partners A, B and C, have a background in successfully collaborating on and completing large scale projects. The SRL case therefore provides an example to analyze a high performing organization failing to complete a complex, high-tech project.

In this study, we use the SRL case to shed more light on why complex high-tech projects frequently fail. Our method is a combination of qualitative data analysis and system dynamics modeling and simulation. System dynamics modeling and tools have been used for decades to look at and understand project management. In Lyneis and Ford (2007), many of the applications of using system dynamics in project management are addressed. One of the most significant and relevant to this investigation is using system dynamics as part of a post-mortem assessment. This is expounded on by Cooper *et al.* (2002) in their discussion of using system dynamics in project management as a tool for learning from past projects. Both Lyneis and Cooper comment on how while the importance of developing more successful project management tools is critical, there is limited success in learning from these lessons in project management. Copper *et al.* (2002, pp. 213) states, “A number of conditions have contributed to and perpetuated the failure to systematically learn on projects. *First* is the misguided prevailing belief that every project is different, that there is little commonality between projects” The analysis of the efforts of the SRL offers a unique opportunity in that the first year of the project has ended and can be analyzed as a post-mortem, but the project will be continuing on and thus the lessons of the first year can be directly applied to the follow on work.

This paper seeks not only to model the project management and performance of the first year efforts of SRL but to build off that understanding to create actionable policy recommendations which can be applied to SRL's ongoing efforts in the second year of this robotics competition and future projects beyond that. By recommending policy and being able to apply that to an ongoing project, this work helps to fill the need for documenting learning from project to project and provides an example of actionable policy that can be applied to future projects.

2. Problem Definition

Over the course of several years, SRL has enjoyed technical success which has resulted in winning larger and larger projects and grants. During this same time period, in order to meet the increasing scale of projects, the lab also grew its ranks by increasing its number of graduate students.

Figure 1 depicts the overall historical trend of the lab leading up to the project as well as the projected hopes and fears of the organization.

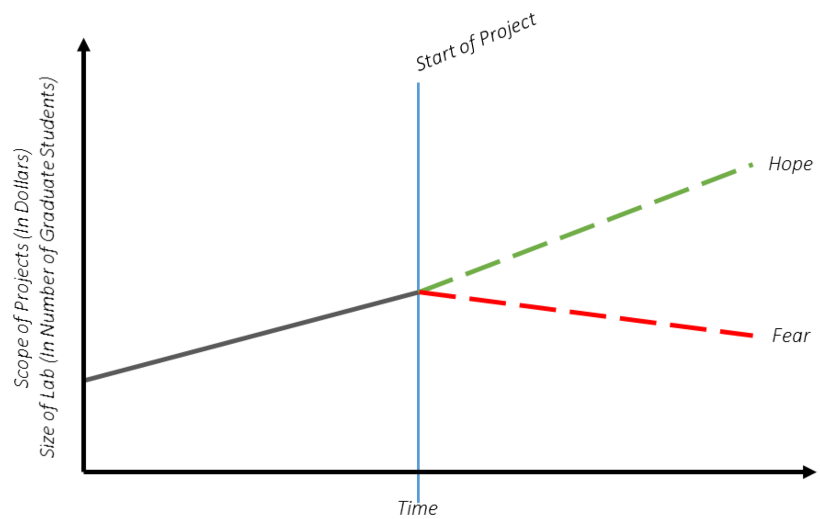

Figure 1: Reference Modes for historical trends in Southeastern Robotics Lab.

Note: No scale of exact numbers is used to maintain confidentiality of organizations involved.

This reference mode demonstrates the hope of the organization that the lab would continue its growth both in terms of future funding opportunities and in its student population. Success in the high profile international robotics challenge would greatly increase the chance of achieving the desired conditions. Conversely, poor performance in the competition could cause stagnation or a decline in the growth of the lab which would be considered a fear of the organization. The lab had demonstrated success in the past, and while this competition was indeed a larger project than the organization had taken on in the past, it was not a significant jump from the growth trend the lab was already on. Despite these past indications of success, the project was unsuccessful and the robotic platform being developed by SRL and its partners was unable to perform in the desired capacity at the end of the first year.

With the failure of the project and the inability to compete in the first year of the competition, the SRL has already begun to see the trend in graduate students and funding trend towards the feared condition, with graduate student retention in decline and limited future funding available without intervention.

In order to prevent the downward trend from increasing, it is critical to understand what dynamics may have caused the failure and what new policies need to be implemented if the SRL is to avoid the feared reference mode.

3. Methods

Modeling in system dynamics has long incorporated qualitative data as an important element in determining key variables and causal links in model-building. In the case of the SRL, a complete transcript of all emails between the lead project manager and principal investigator on the contract are available as well as a series of semi-structured retrospective interviews with members of the project team. Using the tools discussed in Kim and Andersen (2012) these sources of data can be used to generate causal relationships and determine the underlying structure of the model needed for this specific project. This builds off the work of Andersen and Richardson (1997) in using group input in model-building as well as Andersen *et al.* (2012) in using interviews to not only build but confirm model formulation.

The interviews were semi-structured, with a few basic questions used to guide the conversation with individual graduate students. The questions used to guide the discussion can be seen in the table below:

	Questions Asked in Semi-Structured Interview
1	How long have you been with the lab? On which projects have you worked?
2	What does your ideal lab look like?
3	What differences are there between this lab and your ideal lab?
4	How is the lab, as an organization, structured?
5	If you wanted to change the way something in the lab was done, what process would you use to create change?

Table 1: Questions for Semi-Structured Interview

Andersen *et al.* (2012, pp. 258) describe the semi-structured interview to “start with a series of structured questions and then move to a more journalistic approach”. This was the general method carried out for the interviews with graduate students in SRL. The two questions: “What does your ideal lab look like” and “What differences are there between this lab and your ideal lab” are intended to get members of the lab to start speaking about their mental model of the current lab for this project and what problems there are with that arrangement. The interviews were carried out in private with only the interviewer aware of who participated and who gave which response. Some demographic information, such as how long interviewees had worked in the lab, was taken; however, this information along was insufficient to tie specific responses to individuals.

The interviews include responses from nearly half of the members of the lab working on the project and cover an experience range of personnel who had been on the project for less than one year as well as members of the lab with greater than 5 years of seniority. All members interviewed were experts in their area of the project and, by virtue of their participation in the project, are experts in the day-to-day operation of the lab.

The second source of data for building the model of the project management of the lab came from archival data from electronic communications between the lead project manager and the principal investigator on the project. This communication is a rich source of data regarding the lab dynamics over the course of the project and includes more than 100 email chains and is more than 270 pages long, covering 10 of the 13 months of the project. In those roles, the project manager ran the day to day operations of the lab, coordinated the effort between different sub-teams, and provided recommendations and feedback to the principal investigator regarding programmatic changes to the project. The principal investigator held the role of the primary authority figure on the project ultimately in charge of the project vision and execution of high level programmatic decisions.

In Deegan (2009) and Kim and Andersen (2012) two different methods are laid out for deriving causal relationships from textual data. In Deegan (2009) this is done by use of a codebook which provides coders with a series of steps to follow in analyzing policy to determine the causal relationships in documents regarding floodplain management policy. The intention in this codebook is to formalize the coding process and begin to remove variability of multiple coders reviewing the data and inferring different meanings from the text. Kim and Andersen (2012) similarly look at using purposive textual data in case transcripts from Federal Open Market Committee Meetings to generate causal maps based on a grounded theory approach. In their work, Kim and Andersen define a purposive text as follows:

> "First, purposive text data arise from a discussion involving key decision makers or stakeholders in the system under study. The participants in the discussion have a sophisticated knowledge of the system, and their expert knowledge becomes the basis of the causal maps being elicited. Second, purposive text data capture the participants' focused discussion on the system and the problem at hand. As a result, the data frequently depict causally and dynamically rich discussions. Third, the discussion captured in the data should reflect a frank and unfeigned conversation of the decision-making group." (Kim and Andersen 2012, pp. 312-313

The email transcripts between the project manager and the principal investigator meet the description of purposive textual data and provide a different vantage point on the project dynamics from the interview data.

In both Deegan (2009) and Kim and Andersen (2012), the methods for deriving causal relations from the text follow the same basic pattern: determine dynamically rich text, identify the cause and the effect as well as polarity of the relationship, and finally codify this into a causal mapping. In analyzing the interview data as well as the email data, this general pattern for deriving causal relationships from qualitative data will be used by first identifying the dynamically rich topics, identifying the cause and effect and finally codifying the causal mapping from these topics.

4. Analysis of Qualitative Data

The interviews were conducted with members of the lab. The table below shows the different responses and frequency with which each response came up in the description of the "ideal lab."

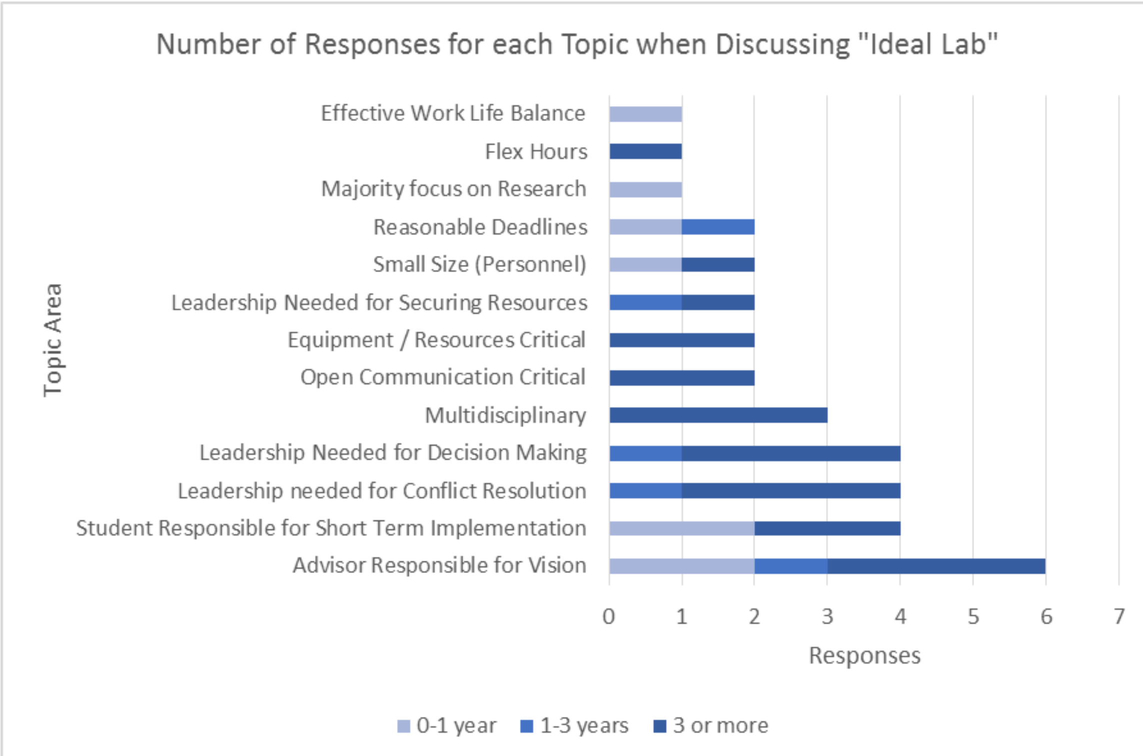

Figure 2: "Ideal Lab" Interview Responses

Additionally, the graph below shows similar data (different responses and number of interviews in which the topic was discussed) for the discussion of the differences between the ideal lab and the current state of the lab:

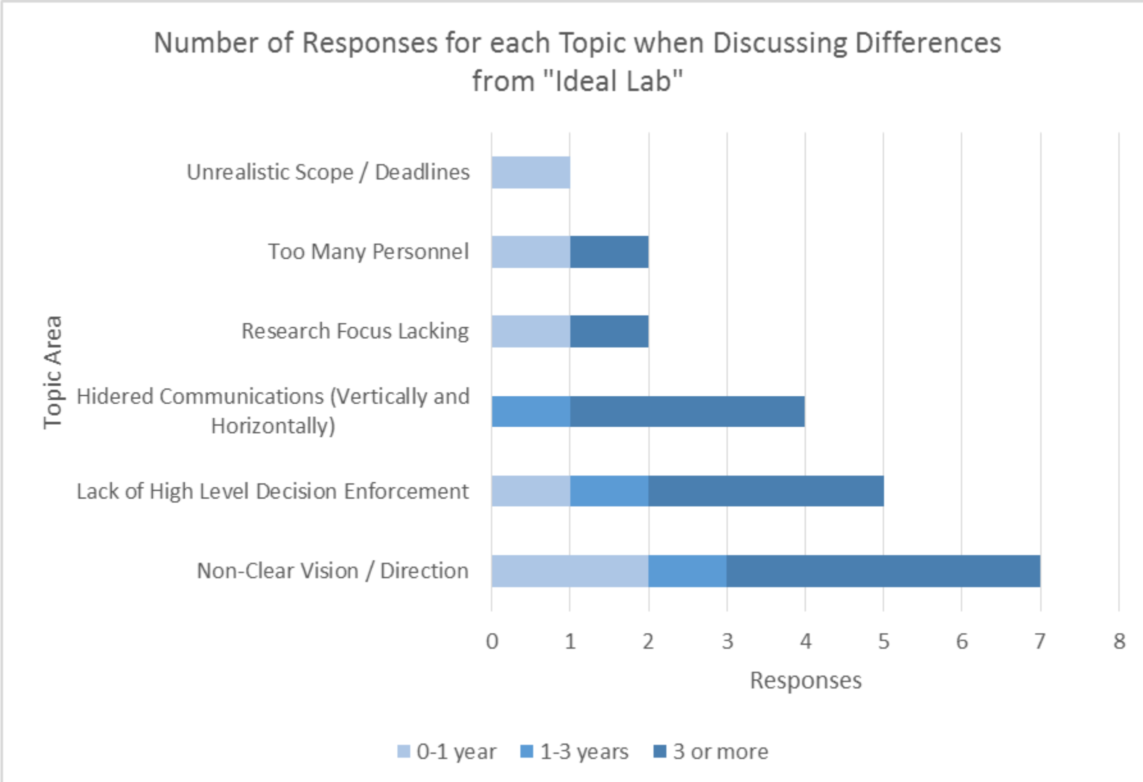

Figure 3: "Differences" Interview Responses

In the first step of determining the causal relationships illustrated in this data, the dynamically significant topics need to be identified. For each question, the total topic areas to be analyzed will be limited to those which were discussed in at least half of the conducted interviews (a cut off of 4 responses or more). This brings the list of topics to analyze to:

- Leadership Needed for Decision Making
- Leadership Needed for Conflict Resolution
- Students Responsible for Short Term Implementation
- Advisor Responsible for Vision
- Hindered Communications
- Lack of High Level Decision Enforcement
- Non-Clear Vision / Direction

From this list of topics, we can clearly begin to see cause and effect relationships which can be summarized in the chart below. In the chart, a cause and effect variable is identified as well as the polarity of the relationship. More specifically, a positive polarity indicates that, everything else constant, as the cause increases, the effect also increases. Similarly, a negative polarity indicates that as the cause increase, the effect would do the opposite and decrease, or vice a versa.

	Cause	Effect	Polarity of Relationship	Evidence
1	Leadership	Communication Decision Making Vision and Direction	+	- Leadership needed for decision making - Leadership needed for conflict resolution - Advisor responsible for vision
2	Number of Students	Productivity	+	- Students responsible for short term implementation
3	Communications	Effectiveness of Effort	+	- Project had hindered communications
4	Decision Enforcement	Effectiveness of Effort	+	- Project lacked high level decision enforcement
5	Vision / Direction	Effectiveness of Effort	+	- Project lacked clear vision / direction

Table 2: Case and Effect Relationships from Interview Data

These cause and effect relationships begin to shed light on the underlying structure of what drives the dynamics of the SRL during the first year of the project. While it is not surprising that that topics like "leadership" and "vision" were discussed, what is significant is what is *not* discussed. There is no mention of the technology being beyond the capability of the lab. There is no mention of a lack of resources, financial or hardware. What the data here begins to show is what the major, driving causal relationships of the system were as they are the significant topics present in the mental model of the majority of the interviewees.

From the chart above, we can begin to generate the underlying causal mapping of the lab dynamics during the first year of the project:

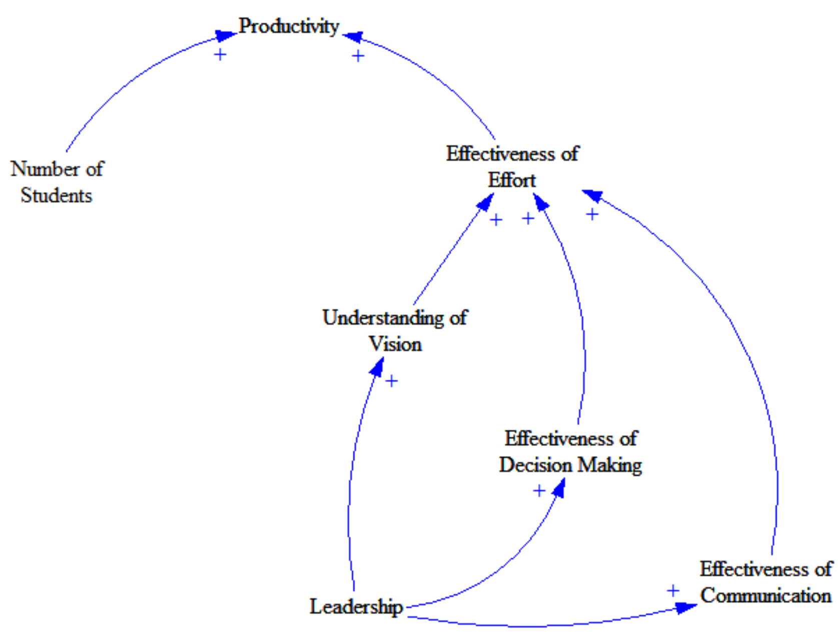

Figure 4: Causal Mapping from Interview Data

Moving on to the data from the emails between the project manager and principal investigator, this same procedure can be followed to determine the mental model of project leadership and see how that compares or adds to the model elements derived from the interviews. The entire body of emails were divided up so that each chain of emails (one initial email and all subsequent replies or forwards) was treated as a single element. From there, the emails were broadly encoded based on the subject matter of the email chain. In doing this, 80 different incidents were discussed over the course of 10 months. The series of incidents discussed collapses down into eight broad categories of issues or problems:

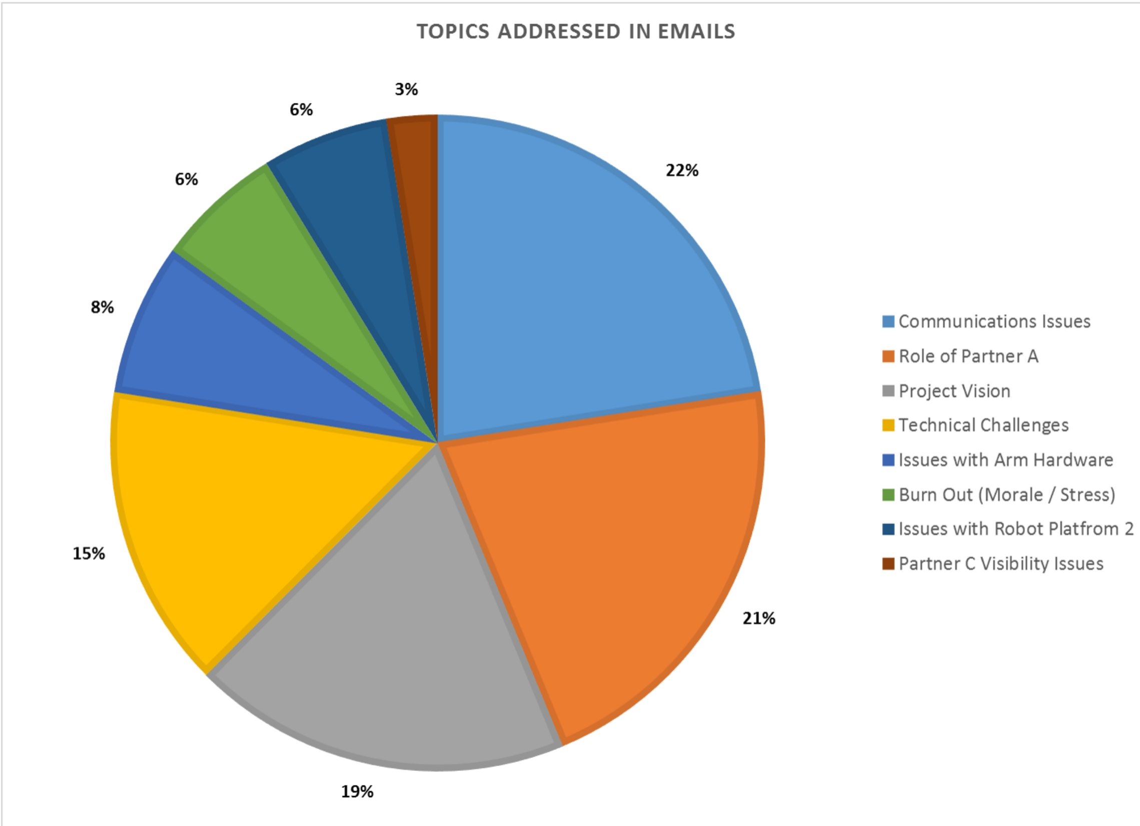

Figure 5: Breakdown of issues discussed in email during the project

Looking at the breakdown of issues discussed, it is clear that four topics drove the majority of discussion: communications issues, the role of Partner A, project vision and technical challenges. This matches with the underlying themes gathered from the interview data as well with more than half the topics discussed being related to communication, vision and direction of Partner organizations. Again we see that technical challenges, resources and hardware were factors in the project but not dominant or driving factors.

To further analyze the qualitative data from the emails, each email chain was coded for key words, sentences, and paragraphs, and relevant dynamic hypotheses were gathered and further codified into cause and effect variables with annotation related to their polarity (consistent with Kim and Andersen’s (2012) method). An example of the method used is shown below to illustrate how the other quotations were encoded. Brackets have been used to remove names or other specific information and indicates where text from the original email has been changed:

> *I wanted to reach out to you with some of the pitfalls that I see on the horizon so we can begin to take measures to avoid them. I think we are reaching a critical point in the project. Up to now the information from [Contractor] has been vague and I think a lot of our communication and development has all been at a very high level. As CDR gets closer and closer [Contractor] is quickly beginning to solidify it's expectations and it's documentation. In the next few weeks it is critical to the success of the project that we rally and really nail down the details of the software system.*
>
> *It has become clear to me that there is still a pretty substantial amount of uncertainty with the software side of the project. I think this is illustrated by some of the conversation yesterday at the Software Meeting and then again at the Planning meeting. I think there is uncertainty about how each player's piece is going to mate up with the others and I think as you've stated a few times now, that there are duplicate efforts.*
>
> *I think it's unavoidable that there will be duplicate efforts for a variety of reasons which are unavoidable. Given that more than half of this project is being done by grad students I think a lot of people's contribution to the project are tied up in their research / thesis and so duplication with defining the inverse kinematics or doing grasp behaviors are often part of their larger work.*
>
> *That being said- these duplicated efforts do not make good CDR demos nor are they critical to the overall success of the project.*

Cause	Effect	Polarity	Notes
Direction	Communication	+	A lack of direction is leading to uncertainty about team member's roles
Communication	Effectiveness of Effort	+	Poorly communicated roles lead to duplication of effort
Effectiveness of Effort	Project Completion	+	Duplicated efforts limit productivity moving forward

Figure 6: Example Cause and Effect coding from email quote

In the quote from email above, we see a chain of cause and effect variables and the polarity of their relationship. A lack of direction ("a… substantial amount of uncertainty") has caused a breakdown in communication ("this is illustrated by some of the conversation yesterday…") which in turn creates duplication of effort which reduces the productivity of the overall project effort ("these duplicated efforts do not make good CDR demos…"). Thirty-two excerpts were analyzed, each adding at least one cause and effect relationship. From the variables and causal relationships identified in the email excerpts, the following mapping can be drawn:

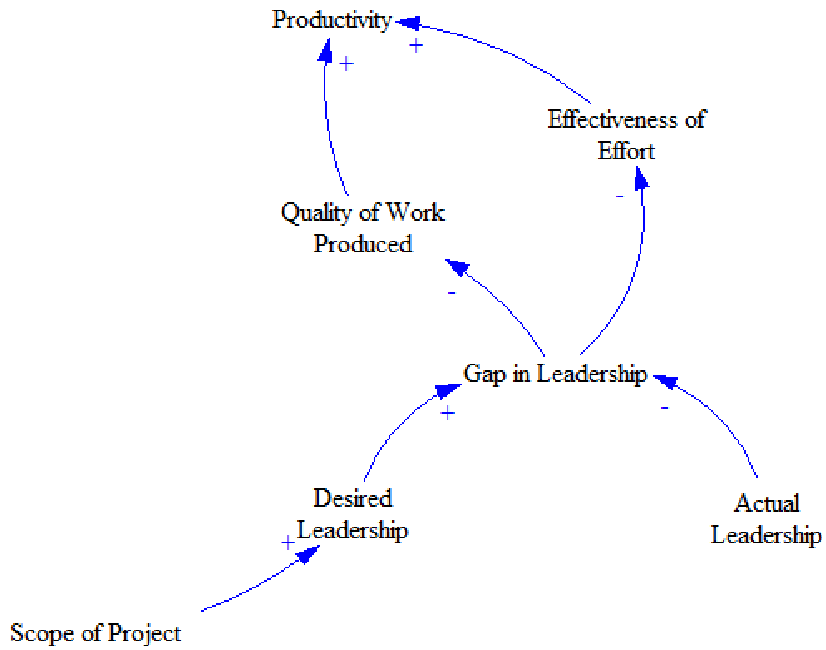

Figure 7: Causal Mapping from Email Data

Similar to the causal mapping from the interview data, this does not provide a complete model of the dynamics of the lab but instead provides a critical piece of the model. In Kim and Andersen's (2012) method, the next step involves stitching the model elements generated from analysis of the data segments into a single causal map. In the next section, the structural elements derived from the interview and email data will be augmented with common canonical elements of project management models discussed in Lyneis and Ford (2007) and others to provide a complete model which can be simulated and used for recreating and analyzing the lab dynamics during the first year of the project.

5. Structure

Using modeling tools and system dynamics to simulate project performance project management has been discussed my numerous studies such as Cooper (1980), Abdel-Hamid (1988) and (1990) as well as many other. At the heart of our system dynamics model of project management is the canonical structure for the rework cycle (Lyneis and Ford 2007). The rework cycle, at a high level, is the mechanism by which some initial quantity of work or "job units" are tracked to completion signifying project progress in the simulation. The rework cycle includes the concept of "rework" or project tasks that are done incorrectly the first time or that become obsolete or irrelevant by changing needs and interfaces in the project (Lyneis and Ford 2007). The first rework cycle is attributed to Richardson and Pugh (1981), with variants of the rework cycle being used multiple times across the literature on system dynamics in project management. In modeling the work of SRL, the re-work cycle is based on the model in Rahmandad *et al.* (2008), as can be seen in Figure 8.

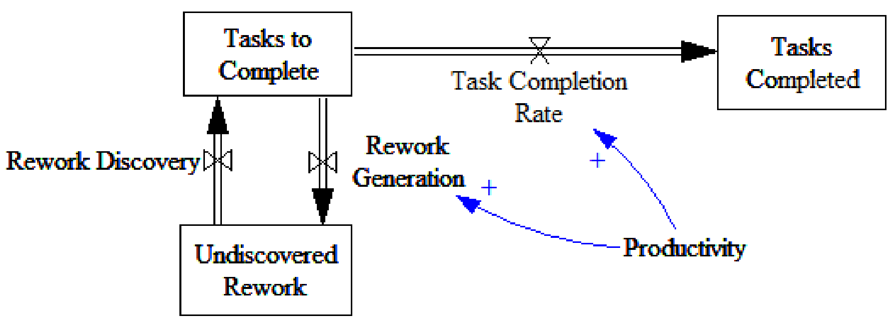

Figure 8: Rework Cycle as used in modeling SRL project based on Rahmandad et al. *(2008)*

In this model of the rework cycle, the project starts with an initial number of tasks which are completed at a "Task Completion Rate." At the same time, tasks are diverted from being completed and instead enter the "Undiscovered Rework" stock to signify work that is done incorrectly, not to the specification required or for some other reason must be redone. This undiscovered work is discovered at the "Rework Discovery" rate which then feeds back into the "Tasks to Complete" stock.

To begin to expand the model, we can add in the notion of resources on the project. In the case of the SRL working on the robotics competition during this first year, two of the major resources were *time* (in the form of a hard fixed deadline for the project) and *graduate students*, which make up the lab's workforce. Adding these to the rework cycle, we can generate the first major feedback loops of the model:

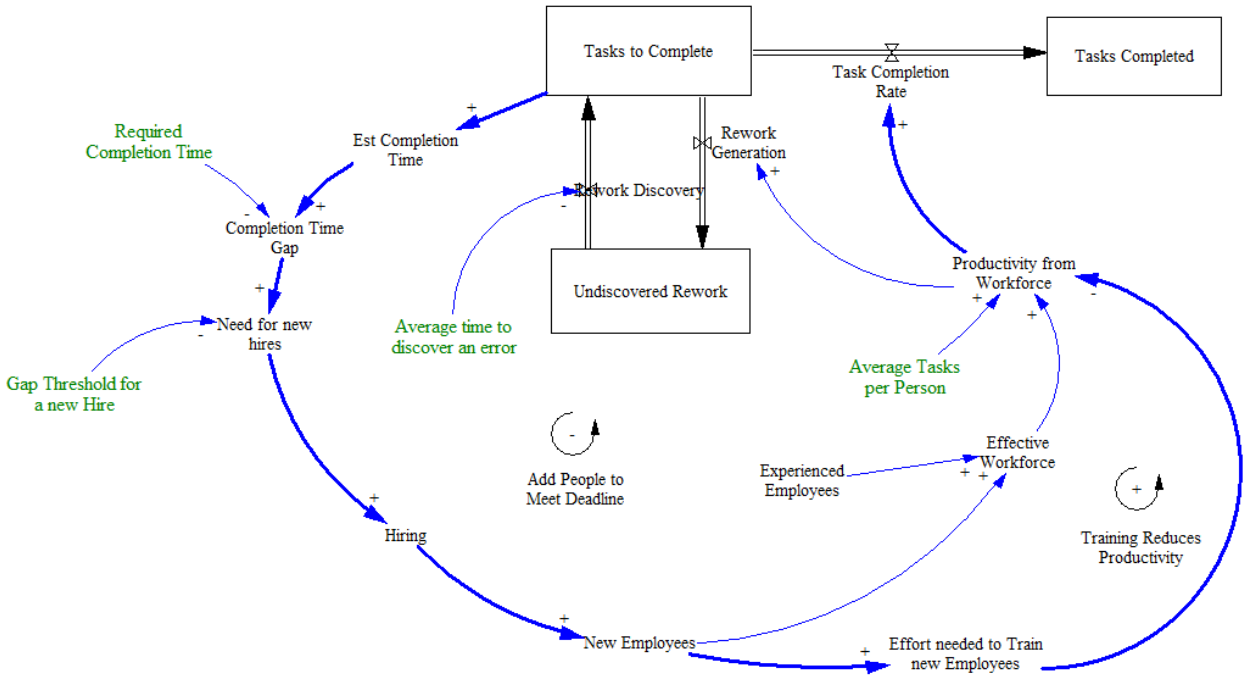

Figure 9: Causal Model of Rework Cycle and Adding People to Meet Deadline and Training Decreases Productivity from Workforce Feedback Loop

This first feedback look in the model shows the management decision-making rule to add more personnel to the project in order to meet a deadline. The second loop included is the impact of new employees on dilution of experience in the workforce. The need to train new employees decreases the productivity of the workforce, since some effort will be diverted from project tasks to training. These loops, like the rework cycle, are common elements in system dynamics model of project management as seen in Lyneis and Ford (2007).

Moving forward, we can now begin to add the causal elements identified in the interviews and email data. There is a relationship between the productivity of the team and the ability for management to articulate a vision or clear set of directions and expectations for the project. From experience and from the interviews, when management is unable to clearly communicate the project direction, the quality of work decreases and thus rework generation increases. Additionally, without a clear direction or without the ability to enforce change and high-level decisions, the effectiveness of the workforce is decreased since they are unable or unaware of how to execute the project. In the model, these concepts of leadership and project management and execution have been distilled down to a single variable: “managerial capacity.” The causal mapping, generated in the analysis of the interview and email data, can now be added to the model to generate two additional feedback loops:

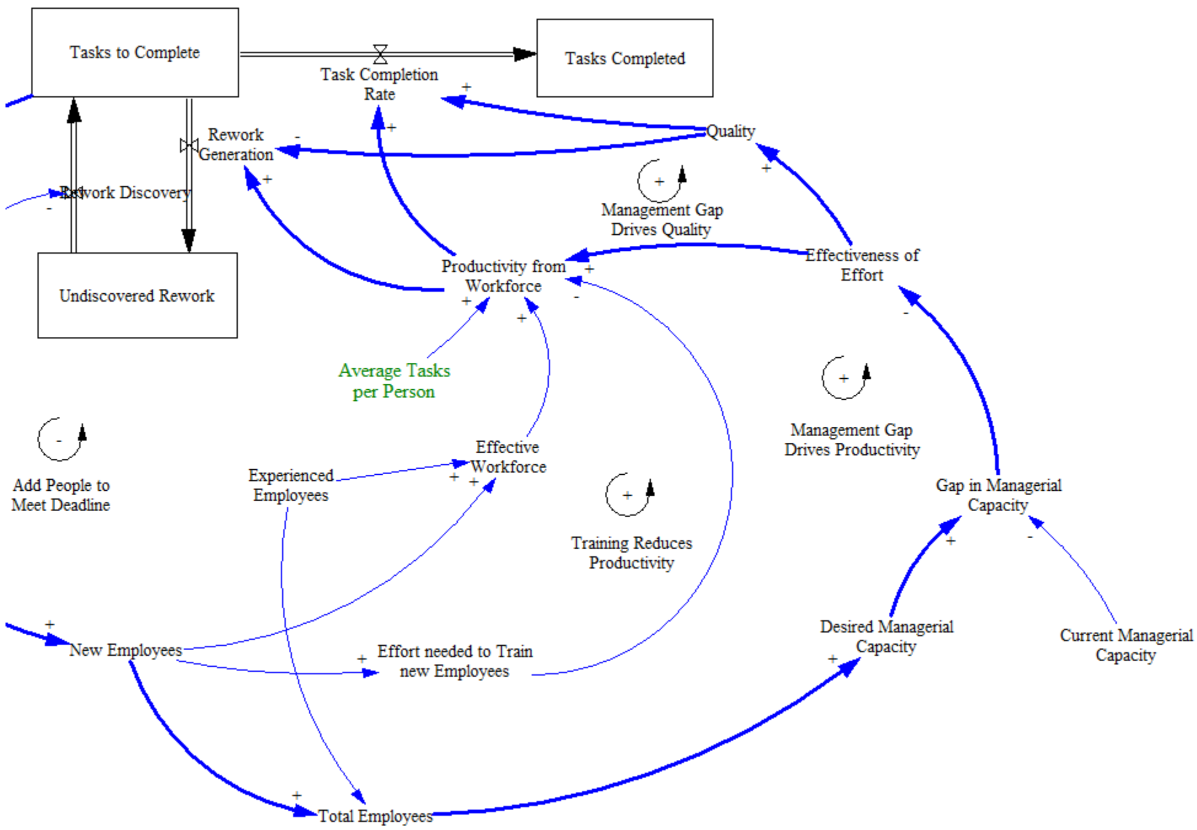

Figure 10: Causal Model of Impact of Managerial Capacity Gap on Productivity and Quality

The figure above begins to move away from the general model provided in Lyneis and Ford (2007) by explicitly showing the role of management in impacting productivity and quality. From the interview data, it is evident that having a clear vision from management as well as the ability for management to enforce project decisions is important and lacking in the execution of the project so far. This lack can be shown as a gap between desired managerial capacity and actual managerial capacity.

As seen in Lyneis and Ford (2007), there are many other feedback loops that can be added to the model, including discussion of morale of employees, availability of financial resources, and the impact of external forces such as clients' and shareholders' opinions of the project or schedule. These additional loops have been left out of the model intentionally since they did not feature prominently in the analysis of the qualitative data for the first year of the SRL robotics competition. The four main loops contained in the model above can be seen as taking the general model for project dynamics and distilling the model down to the primary forces acting on this specific project as determined by the analysis of the qualitative project data. Explicitly, the primary feedback mechanisms of the model are as follows:

1. **Add People to Meet Deadline** – a balancing loop which is driven by the required time to complete the project and by the threshold for making a new hire which adds new employees into the system through hiring.

2. **Training Reduces Productivity** – a reinforcing loop which effectively dilutes the productivity of the workforce. New hires are not as productive as old hires and in fact decrease productivity initially since they require effort to be reassigned to training and away from the project.
3. **Management Gap Drives Down Quality** – a reinforcing loop in which a gap between desired and actual managerial capacity leads to a breakdown in communication and authority, whereby more mistakes are made or what is produced is not well aligned with the overall project or its goals.
4. **Managerial Gap Drives Down Effectiveness of Effort** - reinforcing loop in which a gap between desired and actual managerial capacity weakens management's ability to make and enforce decision and communicate the vision or high level goals of the project. Without management's ability to make and enforce decisions across the project, efforts are unaligned. While a lot of work may be getting done, if that work is not aligned or compatible with the overall project, it is not contributing to the project completion and therefore makes the group productivity less effective.

We can now use the data and initial causal diagrams to further develop a simulation model. The core of the model showing the re-work cycle can be seen in Figure 11.

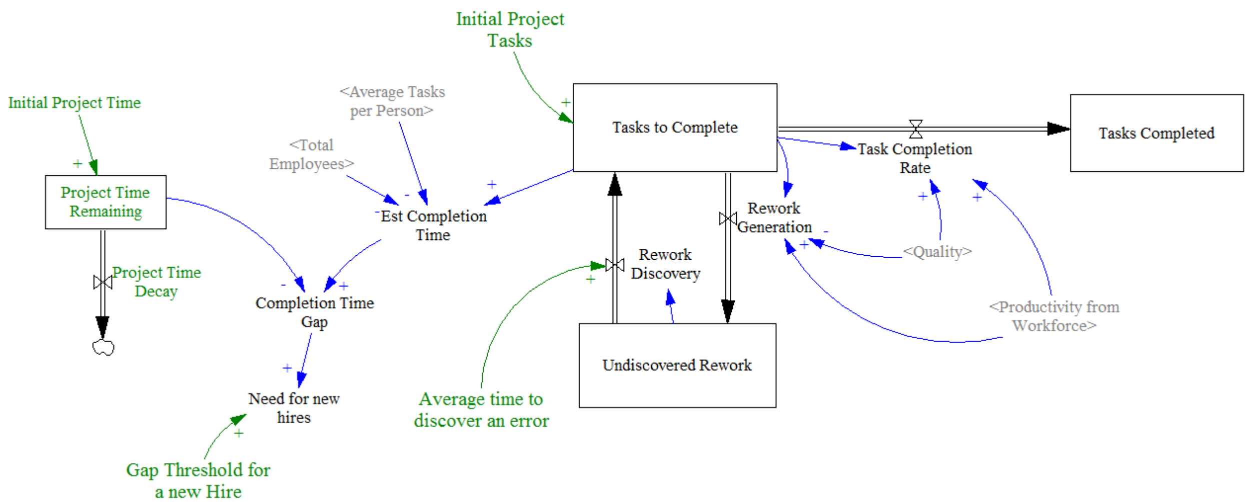

Figure 11: Rework and Deadline Section of Simulation Model

At the center of the model is the re-work cycle being acted upon by "quality" and "productivity from work force" and driving "estimated completion time." As in the causal mapping, "quality" and "productivity from workforce" are defined in other sections of the model but appear here as inputs to the "task completion rate" and "rework generation rate." To model the deadline and decision making process for a new hire another stock, "Project Time Remaining" was created to keep track of time remaining in the project. The need for new hires is driven by the gap between the actual time remaining in the project and the estimated time required for completion of the project.

The estimated completion time is a function of the known "tasks to complete," the number of employees on the project and the average task completion per person rate. The variable "Need for new hires" is the step input into the "Add people to meet deadline" loop, which triggers a new employee to be added to the appropriate stock.

The second section of the simulation model contains the mechanics of the personnel resources, the mechanics of training, and its impact on productivity as shown below:

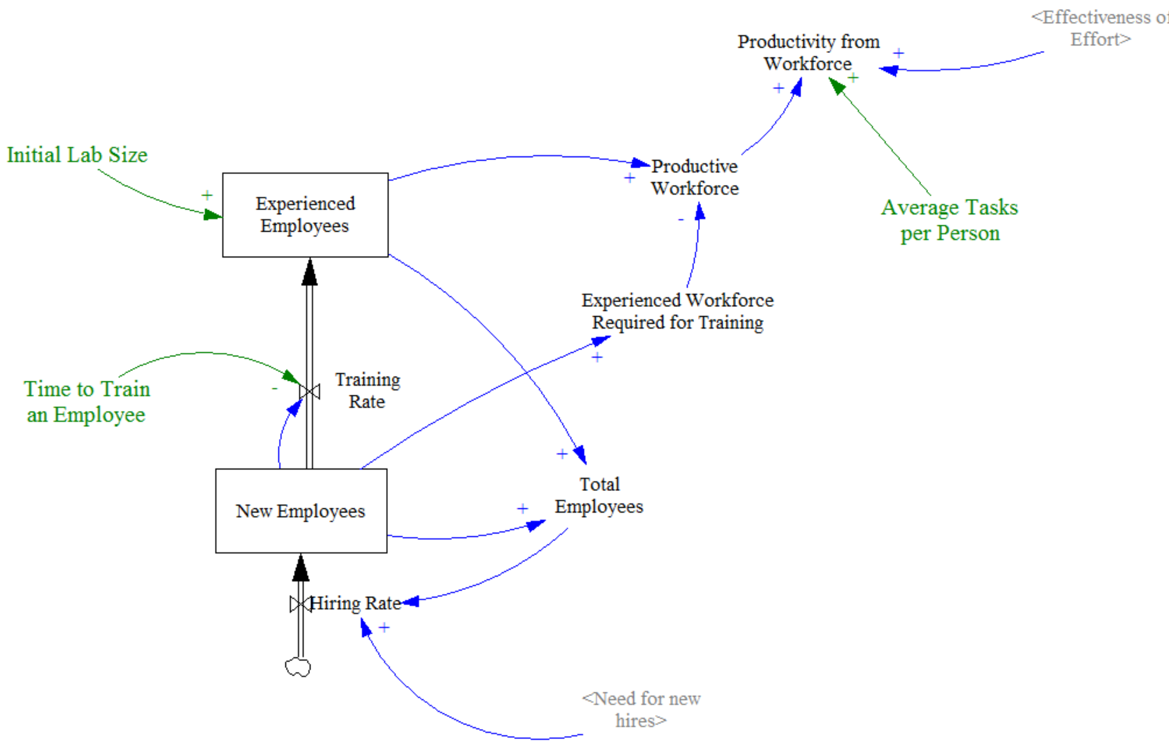

Figure 12: Personnel Resources and Training Section of Simulation Model

Here the concept of experienced and new employees from the causal mapping has been modified into two stocks with a flow, signified as "training rate," between them. The extrinsic variables of "initial lab size," "time to train an employee," and "average tasks per person" are all based off of data collected throughout the project. The "training reduces productivity" loop from the causal map is captured here through the "experienced workforce required for training," which decreases the "productive workforce" based on the number of new employees who remain untrained. During the period of the project, no graduate students graduated; thus, the model explicitly does not have a mechanism for decreasing the number of employees such as firing or retirement, since these don't fit the scenario of a graduate research lab.

The final section of the model captures the managerial gap and its impact on effectiveness of effort and quality.

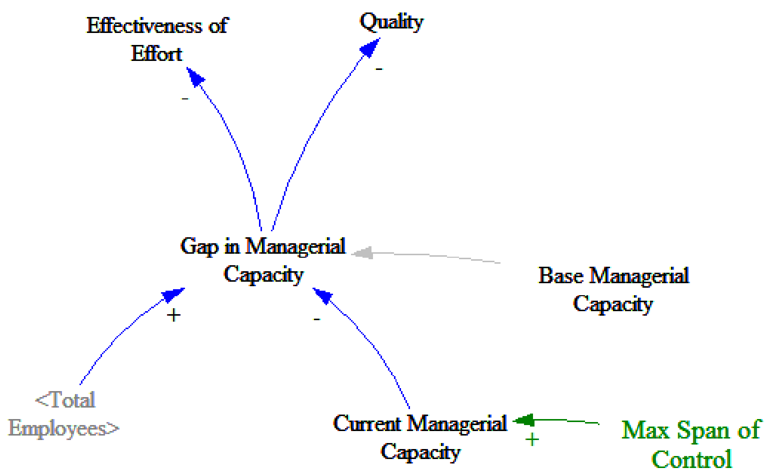

Figure 13: Managerial Capacity Section of the Model

Here, the concepts of managerial capacity and the impact of a gap in managerial capacity are captured. "Current managerial capacity" is determined by taking the number of managers currently on the project and multiplying it by the maximum span of control of a given manager. The variable for "span of control" represents that a given manager can only oversee a finite number of subordinates, and thus finite project size, effectively. While this number can vary from project to project and based on the specific manager and specific team, it is reasonable, based on past lab projects and experience, to assume this value is between five and nine. "Current Managerial Capacity" is compared with the total number of employees currently on the project to determine what the gap between managerial capacity and desired managerial capacity. This value is captured in the variable "Gap in Managerial Capacity." This then feeds into the effectiveness of effort and quality, both of which are formulated using the depicted table functions in Figure 14 and Figure 15.

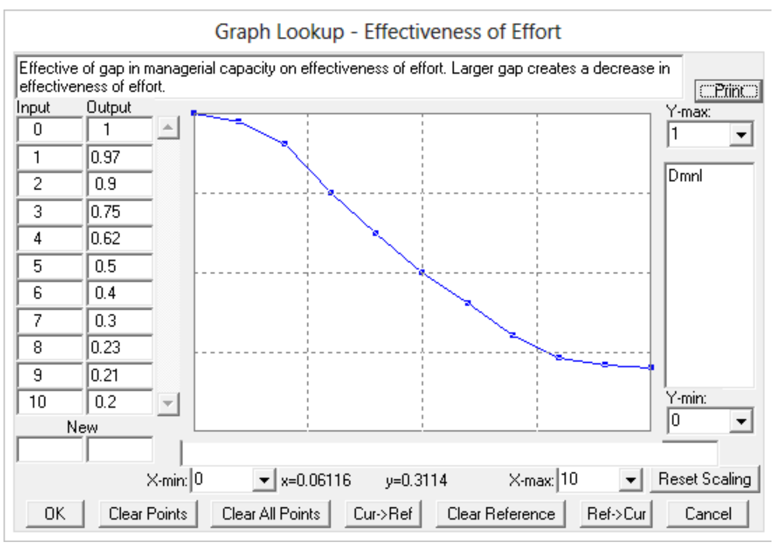

Figure 14: Lookup function for Effectiveness of Effort

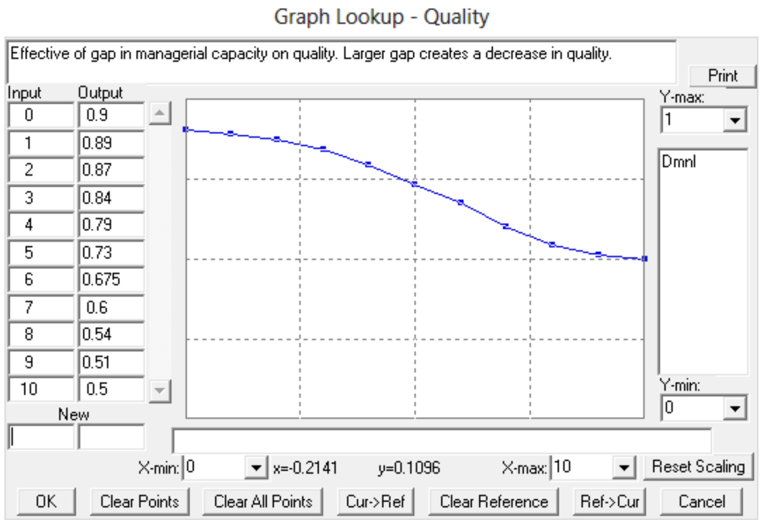

Figure 15: Lookup function for Quality

This section on the model also contains the main structural elements responsible for the remaining two main feedback loops: "Management Gap Drives down Quality" and "Management Gap Drives down Effectiveness of Effort."

6. Simulation Results

After building the simulation model, the model was tested to verify that the system output were reasonable to extreme and equilibrium inputs. As expected, with an initial number of tasks at zero, the system remains in equilibrium and does not evolve. Similarly, with an initial number of employees at zero, several are hired initially and over time become more experienced and begin to complete project tasks as expected.

Three basic modes of behavior can be explained and anticipated by the feedback loops built into the model. In starting to look at the model, the most straightforward variable to look at is the level of the stock: "Tasks to Complete." The plot below shows the value of "Tasks to Completed" for each of the three modes of system behavior:

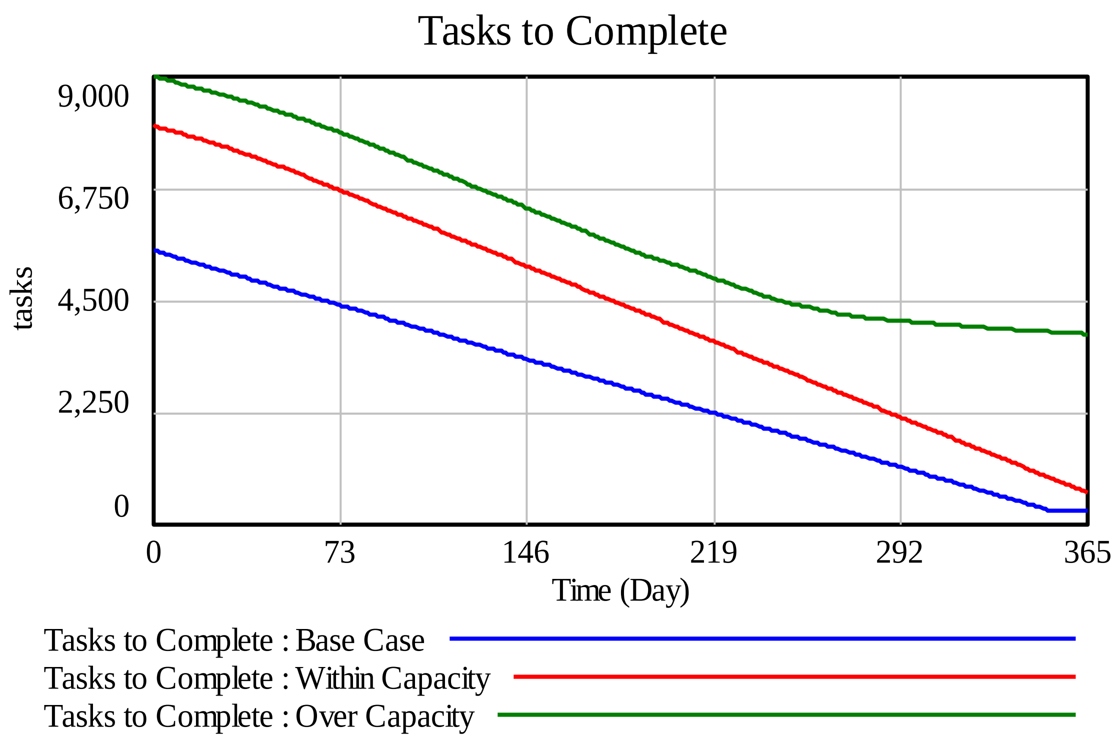

Figure 16: Three modes of "Tasks to Complete"

In the above simulations, the number of initial tasks were slightly increased from run to run while all other parameters in the system were left the same. In the base case, we see a project in which the project team completes all project tasks within the given timeline and does so at a nearly constant rate. In the second case, the initial number of tasks is increased and the hiring process adds personnel to the project to meet the increased workload but is still within the managerial capacity of the lab. This increases the slope of the line as expected, and the project completes close to on time (there is a 5% dead band in the model to shut down the flow of tasks before being negative). In this second case, called "Within Capacity," the model responds as expected: the project requires more resources than needed initially on the project, a new member is hired, and the total number of employees remain with the managerial capacity; thus, the system behaves by an ultimate increase in productivity.

In the third case, we see the replication of one of the reference modes discussed in the beginning of the report: productivity stagnating and the number of tasks to complete also stagnating and missing the project deadline by a significant amount. The increase in initial tasks is small compared to the difference in the final state of “Tasks to Complete” when comparing the second and third case. This third case, called “Over Capacity,” is driven by the ripple effect caused by the total employees on the project being greater than the managerial capacity of the lab. As expected based on the feedback loops in the model, once the number of employees on the project is greater than the project can manage, the secondary effects of the managerial gap on productivity and quality begin to take effect.

As expected, since both of those loops are positive, the initial decrease in productivity continues to grow. This loss in productivity moves the set point of the hiring loop by increasing the estimated completion time which adds more employees to the project and this continues to exacerbate the gap in managerial capacity. This effect is more clearly seen looking at the total number of employees over the course of the project:

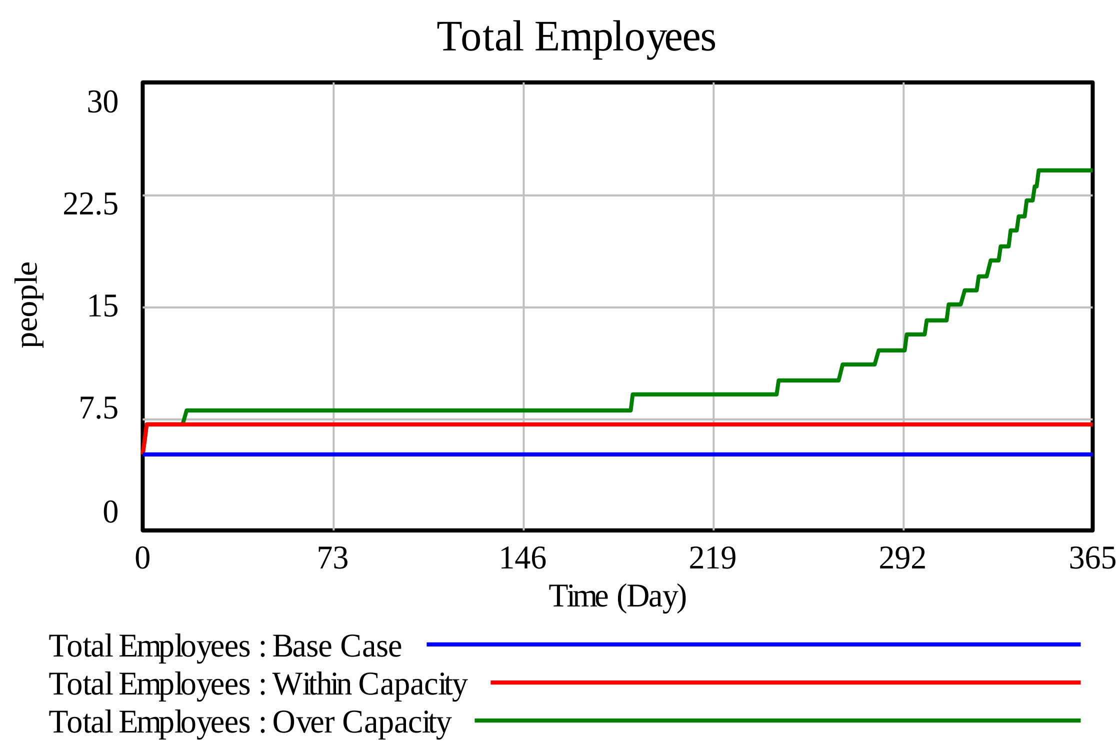

Figure 17: Three modes of Total Employees

Here, the same three simulation runs can be seen with the clear differences in the total number of employees assigned to the project. The “Over Capacity” case results in a growth of employees as more and more personnel resources are assigned to the project to try and close the gap between estimated time required to complete the project and time remaining in the project.

The third set of plots needed to really understand the behavior of the system is contained in the behavior of the "productivity from workforce" variable as can be seen below:

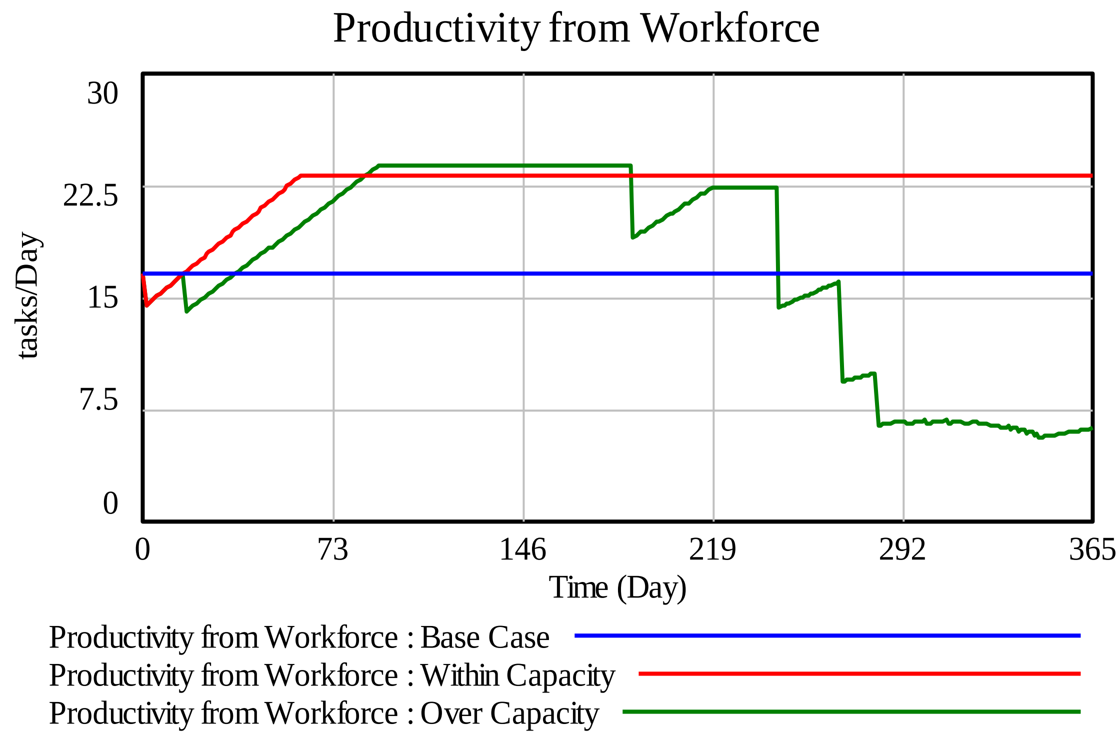

Figure 18: Three Modes of Productivity from Workforce

Looking at the "Productivity from Workforce," the ripple effects of the different feedback loops can be observed on the output of "Productivity from Workforce." Looking at both the "Within Capacity" and "Over Capacity" cases, there is an initial drop in productivity that corresponds with a new employee being added to the project. This initial drop is overcome as the employee is trained, and in the "Within Capacity" case and in the beginning of the "Over Capacity" case, this ultimately increases the productivity of the team.

In the "Over Capacity" case, the system has a tipping point tied to the initial number of project tasks where the additional mechanics of the feedback from the gap in management begin to impact productivity through the "Effectiveness of Efforts" variable. This impact is layered on top of the "Training Reduces Productivity" loop's impact on productivity, as each new employee still causes an initial decrease. The "Effectiveness of Effort" then decreases the steady state value to which productivity rebounds.

The original problem statement for this report was to understand why the project was less successful than hoped for in the first year of the project and what can be done differently to prevent a similar failure mode in the future. The simulation model takes into account the key variables and behaviors discussed in coding the interview data with members of the project team and combines that data with the general model of project management in

Lyneis and Ford (2007) to build a model specific to the situation that unfolded for the project team in the first year of the project.

The simulation model's performance matches the expected behaviors and reference modes expected for task completion and hiring. Additionally, and more importantly, the model produces behaviors that closely model the decisions made by the project team and the experiences of the first year of the project. These are reflected in a ramp up in hiring as the project went on and a dramatic decrease in performance, leaving the project farther from completion than expected.

Additionally, the model also shows how it is possible that the project team had been successful in the past and in fact growing successfully, only to experience dramatically different results on this project than on past projects. The three different modes of behavior from the simulation show that an organization can grow successfully within a given managerial system until a tipping point occurs where the scope of the project and thus the size of the team exceed managerial capacity. This tipping point causes ripple and knock on effects to the performance of the system which are not easy to directly detect and do not show themselves explicitly. In the "Over Capacity" case, it is not clear at the beginning of the project that the overall project will behave any differently than the "Within Capacity" case. This is significant because it represents a mode of behavior that will ultimately lead to failure of the project but in a method that is difficult to detect early on.

7. Policy Recommendations

The simulation model as it is now only addresses half of the problem statement for this report. The second half of the problem statement, "what can be done differently to prevent a similar failure mode in the future," requires an additional decision-making rule to be modeled into the system to allow for additional managerial capacity to be added to the system.

In order to create this decision-making rule, the ideal goals and outcomes must be identified:

- Adding additional management should be done as late as possible (since in practice adding additional management normally requires additional financial recourse and additional overhead)
- Adding additional management should prevent the exponential growth of employees on the project
- Adding additional management should prevent the stagnation of task completion, allowing the project to finish significantly closer to the desired completion date

In order to make this new decision rule a part of the simulation model, it must also follow the basic principles for modeling human behavior stated below (Sterman, 2000, p. 517):

1. The inputs to all decision rules in models must be restricted to information actually available to the real decision makers
2. The decision rules of a model should conform to managerial practice
3. Desired and Actual conditions should be distinguished
4. Decision rules should be robust under extreme conditions
5. Equilibrium should not be assumed.

Looking at the model of the project so far, the major loops which drive the failure of the project are in turn triggered by the gap in managerial capacity. While the total number of employees on the project can be measured, the actual span of control of the management assigned to the project cannot, and thus the gap in managerial capacity itself cannot be directly measured.

Continuing around the loop, we come to the effect the managerial gap has on the "need to new hires" variable. By decreasing the productivity of the team and increasing the amount of rework generated by lower quality work, the gap in managerial capacity affects the decision-making rule to hire new employees based on a perceived gap in schedule. In this mechanism, the number of known tasks to complete is a measurable quantity, as is the time remaining in the project. Further, the practice of estimating schedule in a project is a common, well accepted practice within management.

Looking at the hiring process as an input into our management hiring loop, its validity can be evaluated against Sterman's principals for modeling. Since the decision to hire a new employee itself follows the Baker Criterion, if the hiring information for employees is used as the input to our management hiring rule, it too will meet the Baker Criterion. Estimating gap in schedule and adding additional personnel to a project is a common and accepted managerial practice. Further, using the hiring rate to determine the need to hire new managerial capacity doesn't assume equilibrium and clearly differentiates between actual and perceived values.

Looking at the "Over Capacity" case and specifically looking at the decision to hire variable, we can see a difference between the behaviors of the variable before the managerial capacity is exceeded and then after. After the managerial capacity is exceeded, there comes a point where there is a dramatic increase in the hiring rate. This can be seen as a "management" crisis, a point at which the fundamental premise of the other management decision-making process, hiring new employees to close the schedule gap, is no longer true because of an underlying management capacity gap. By selecting an appropriate "hiring frequency" ("x" hires / "y" quantity of time) at which to declare a "management crisis," this management crisis event can be used as a trigger to add additional managerial capacity to the project.

Adding this to our previous causal loop mapping results in the following:

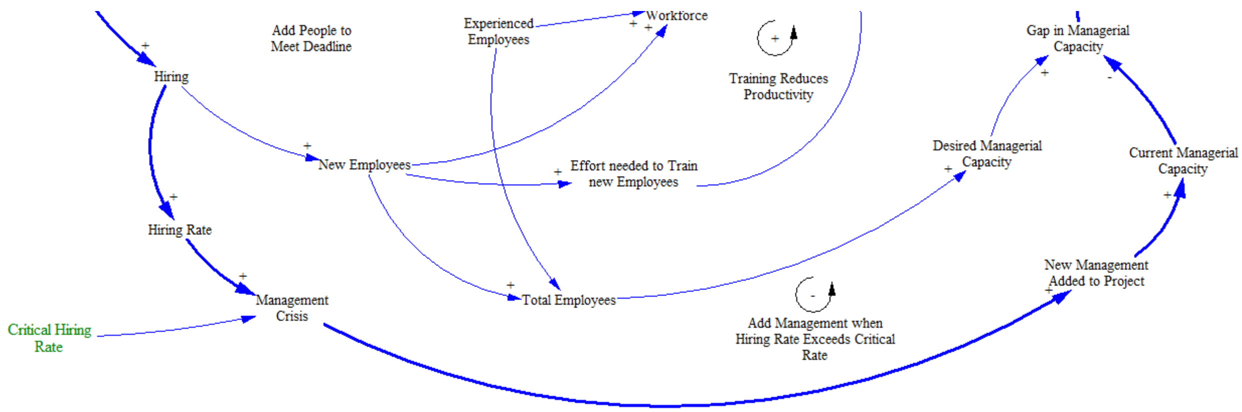

Figure 19: Revised Causal Loop Mapping with Management Control Feedback Loop

The decision-making rule adds new structure and a new feedback loop to the system. By measuring the rate at which new employees are being added to the resource, a "management crisis" is detected, as indicated by the hiring rate exceeding some critical rate. Adding more management capacity to the project decreases the gap in managerial capacity which in turn corrects some of the negative effects, like decrease in effectiveness of effort and degradation of quality.

Taking this new loop from the causal map, we can built it in as a fourth section of the simulation model as such:

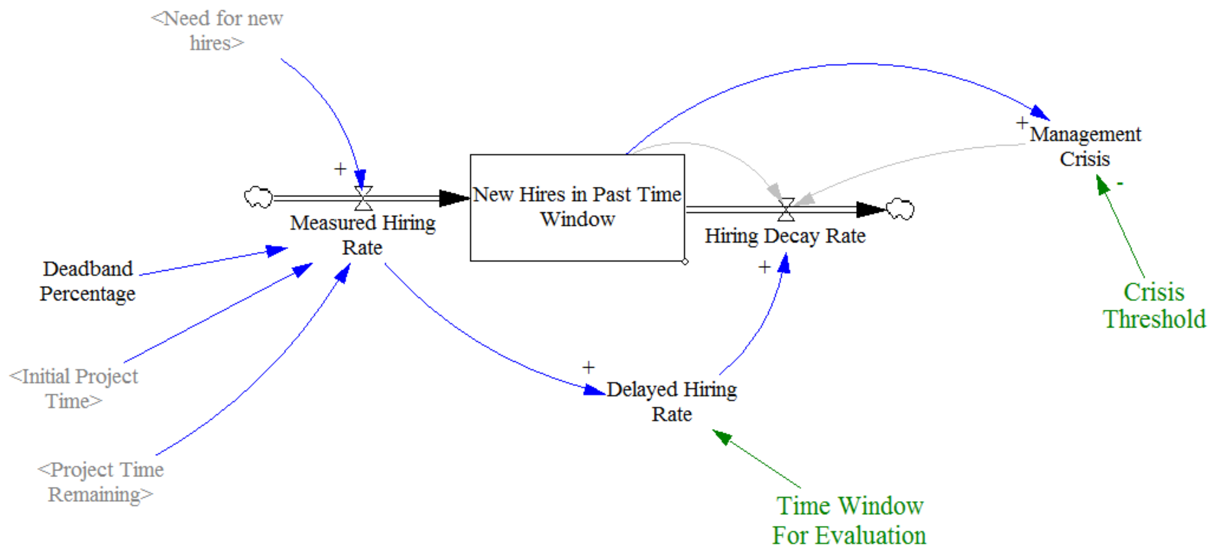

Figure 20: Management Crisis Decision Making Section of Simulation Model

This section of the simulation model has several mechanisms at work. The measured hiring rate feeds into a stock, capturing a measure of all the new hires made in a set time window. The hiring decay rate is the measured hiring rate signal delayed by the variable "time window for evaluation," meaning that if a new hire occurs on day 7 of the project, it will be added to the stock on day seven and removed "n" days later, where "n" is equal to the value of "time window for evaluation." The "management crisis" term checks to see if the current number of hires in the past time window is greater than some threshold. If a "management crisis" is detected, the "hiring decay rate" is set equal to the current value of the "new hires in past time window" stock resetting the measurement Additionally, if a management crisis occurs, another manager is added to "current managerial personnel," thereby decreasing the managerial gap on the project.

Through trial and error, it was determined that a time window of sixty days and a crisis threshold of two hires in that time window produced reasonably robust performance to a range of initial conditions and did not seem to prematurely add management to the project. The plots below show the same set of variables from before: "Tasks to Complete," "Total Employees," and "Productivity from Workforce," now with the management crisis feedback loop applied to the previous failure mode with all other variables left constant:

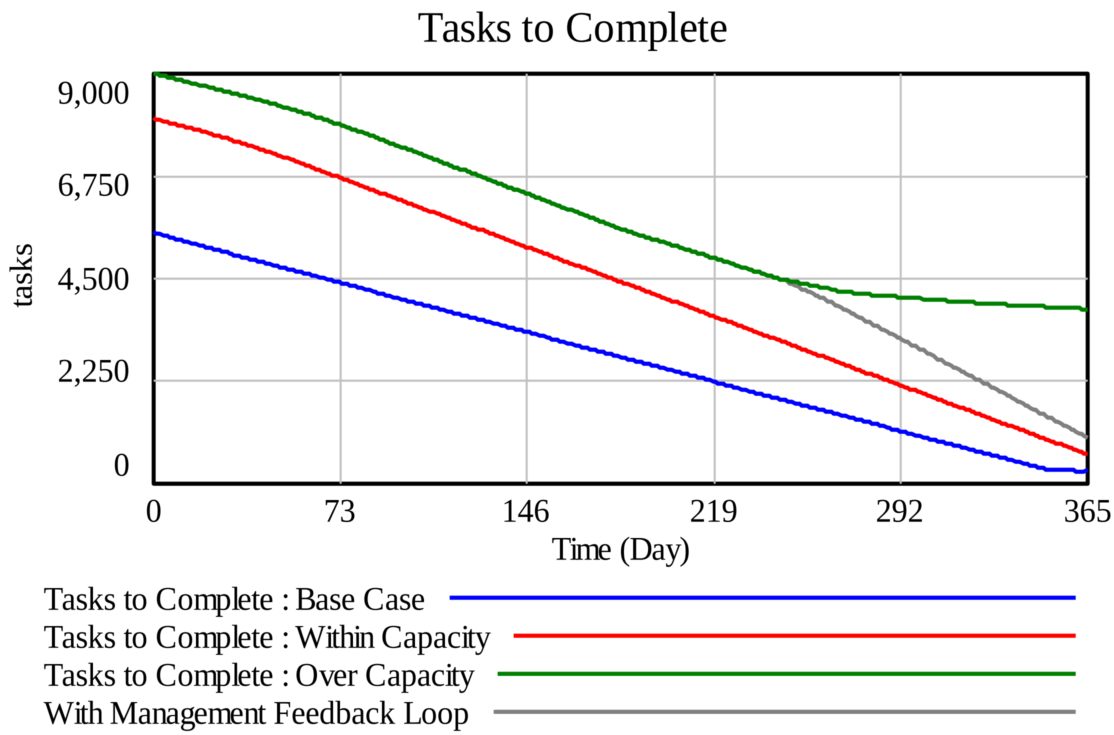

Figure 21: Task to Complete Behavior Modes with Management Feedback Control Added

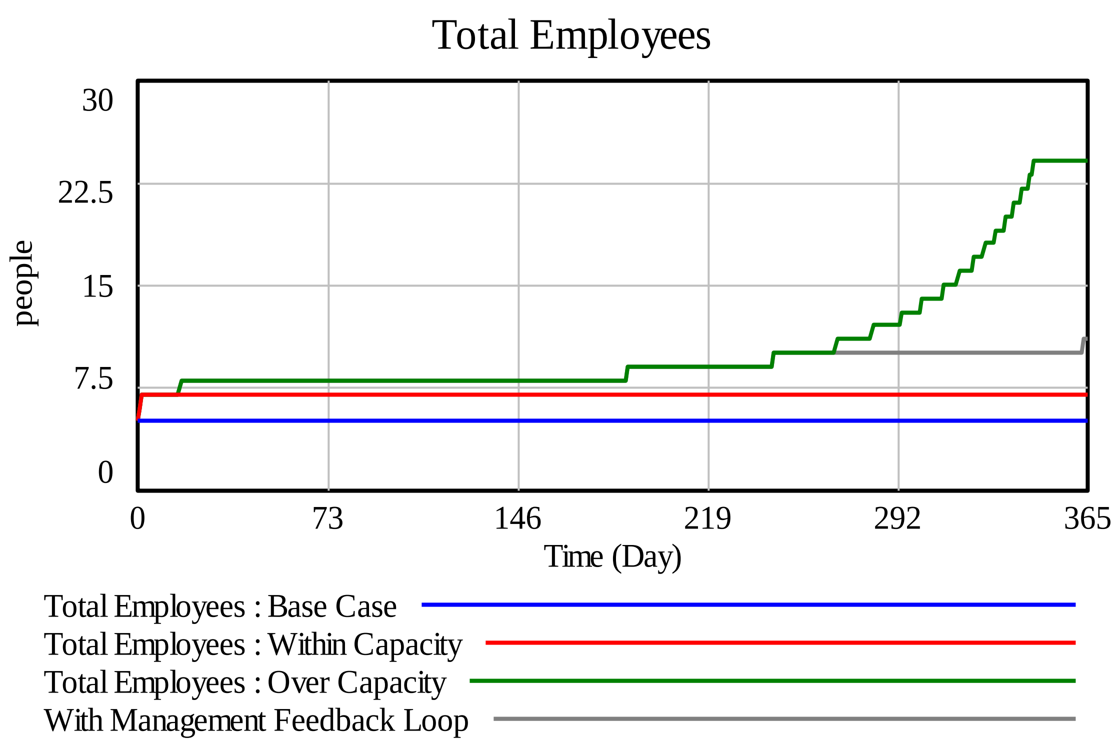

Figure 22: Total Employee Behavior Modes with Management Feedback Control Added

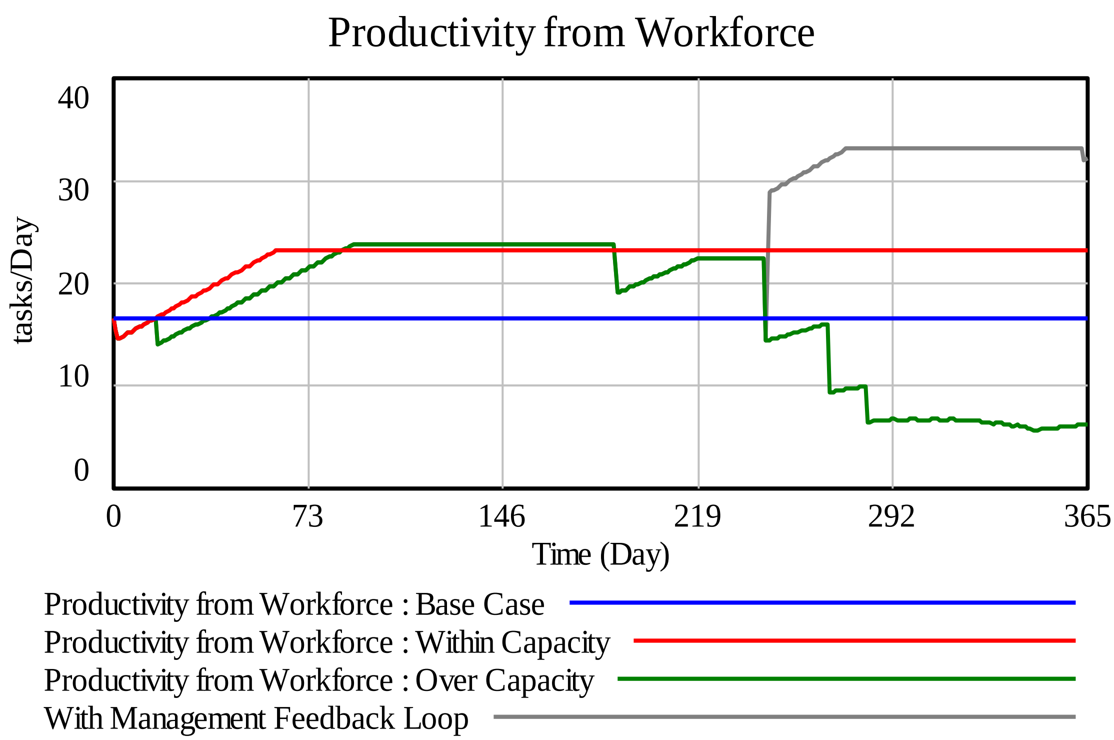

Figure 23: Productivity from Workforce Behavior Modes with Management Feedback Control Added

As can be seen in the plots above, the new feedback loop effectively controls the previous reinforcing loops which drove up hiring while driving down productivity caused by a gap in management. Here, the new loop, by looking at the rate at which new employees are being added to the project, responds to the perception of a management crisis and adds managerial capacity to the project and thus stabilizes the system by removing the positive feedback loops created by the gap in managerial capacity.

The plot below shows a number of scenarios demonstrating that the new loop functions for more than the set of values chosen in the previous “Over Capacity” case but for a wide range of initial task levels:

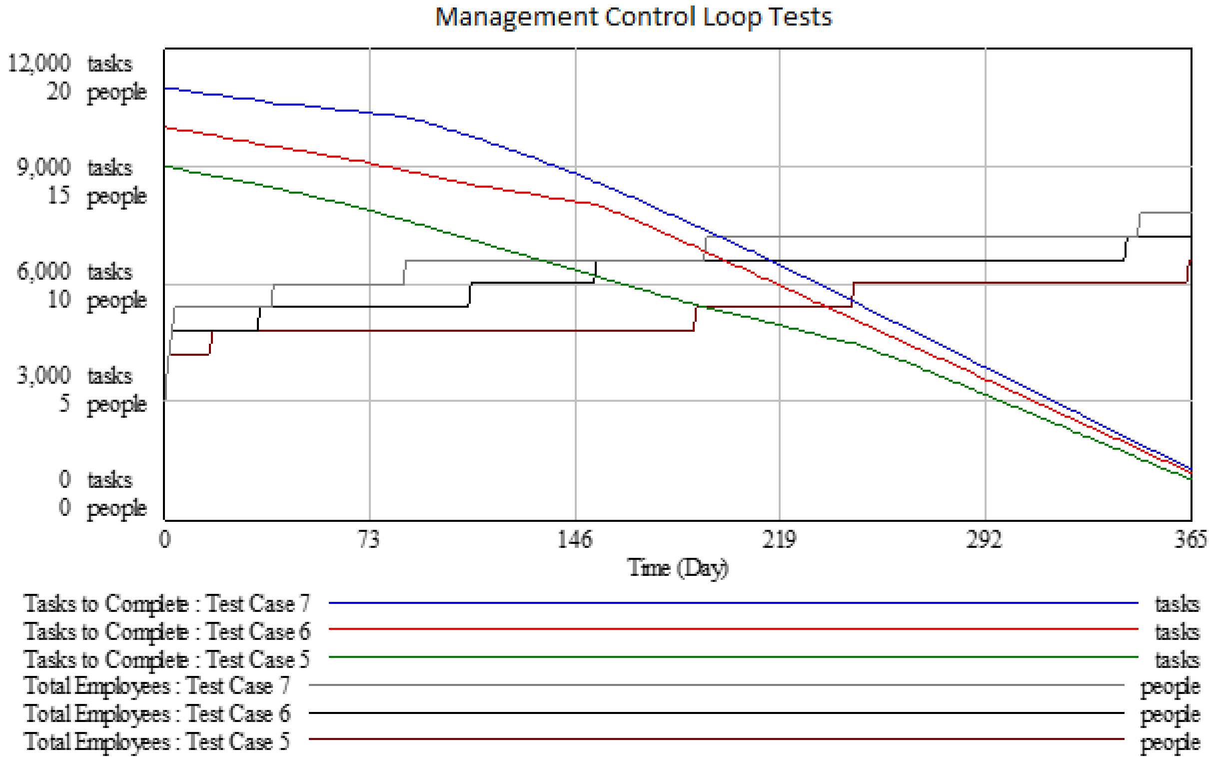

Figure 24: Multiple simulation tests of Management Control Loop using Increasing Initial Task Levels

With the addition of the new management control loop, both of the original objectives of this report have been met: determine the failure mode of the first year of the project and determine a feedback mechanism to prevent a repeat of this failure mode. By looking at the rate at which new personnel need to be hired to the project, the underlying state of management on the project can be inferred. As the project is underway, if the need for more personnel continually ramps up, it is indicative of a need for more managerial capacity on the project to enforce project decisions and provide a clear and executable vision to the project team.

8. Conclusions and Future Work

As the SRL's project enters into its second year, it is vital for the project team to understand what caused the degraded performance in the first year to prevent similar behavior from happening again. By taking interview and email data and applying methods for extracting causal relationships from qualitative data as described in the literature, we were able to generate a mapping of key dynamics of the project team during the first year. This mapping allowed for simulation and testing of new policies to better understand why the project was unsuccessful and what can be learned to prevent similar failures.

While communication is often cited as a key element in project dynamics, the analysis of the SRL case shows clearly the impact the leadership and management have on shaping that communication and the ripple effects that a gap in management and leadership can have on hindering communications and, in turn, effectiveness and productivity. The SRL case also shows how even organizations with a track record of previous success, if pushed beyond a tipping point, without changing the underlying dynamics of the organization, can fail to perform as expected.

While much of this work builds off prior work in the field of system dynamics, it continues to build the body of work for learning from project management success and failure by identifying and modelling the causal behavior that caused the organization to fail to meet its goal. This report goes further by then recommending policy changes to prevent similar failure modes in the future. This policy recommendation to look at hiring rate to determine the need for additional managerial capacity can be generalized and applied to other simulations of project management scenarios.

It is a critical lesson learned that during the growth of an organization, it is equally important to manage the active project as well as organization itself. As can be seen in the simulation model of the SRL, the beginning of both the "Within-Capacity" and "Over-Capacity" response are very similar. Since the mechanism that drives the failure of the "Over-Capacity" case is the gap in managerial capacity, it is not an immediately evident failure, which provides a false sense of progress and underlying health of the project. Organizations must be mindful and build in mechanisms into their organizational structure to detect and counteract these ripple on effects. This paper provides one possible policy mechanism in the form of looking at hiring rate as a leading indicator of a potential gap in leadership and management.

The most immediately relevant future work is to apply this understanding of the organization's underlying structure as well as the recommended policy changes to SRL's efforts as they move forward with the robotics competition. This provides a unique opportunity to apply lessons learned to an ongoing project and be able to measure the effects of policy changes to the actual project. Additional work includes continued refinement of the simulation model as more data from the ongoing project is collected. With additional refinement the recommended policy change of monitoring managerial capacity through hiring practices can be better tested and generalized to test against other projects.

In conclusion, the case study of the first year of the SRL's efforts in the robotics coopetition provides additional insight into why many high tech innovative projects fail. The complexity and lack of ability to directly measure key dynamic qualities such as desired managerial capacity or effectiveness of communications make it difficult for organizations to recognize and adapt to failure modes during the course of the project. This paper shows how analysis of qualitative data such as interviews and email between leadership on the project can be used to determine the driving dynamics on the project and in turn understand the underlying dynamics. By understanding these dynamics, issues such as gaps in management or hindered communications can be made apparent and then directly addressed to prevent future project failure.

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