CAPABILITY TRAPS IN CONSTRUCTION PROJECTS

A Thesis

by

AKHIL AVARAGOLLA PURAVARGA MATHADA

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	David N. Ford
Committee Members,	Ivan Damnjanovic
	Phil Lewis
	Charles Wolf
Head of Department,	Robin Autenrieth

May 2020

Major Subject: Civil Engineering

ABSTRACT

Despite having enough resources, most development projects fail to finish before schedule and within budget. We hypothesize that a possible reason for project failure could be a capability trap. Capability on a construction team refers to resources such as workforce, tools, etc. and their combined ability to get work done. Capability traps are vicious cycles which are formed by a short-term firefighting focus, oftentimes at the expense of training or mandatory downtime, which ends up draining the capacity of the system to accomplish work. The phenomenon of capability traps has been studied extensively under the context of continuous operations. However, development projects are discrete time-bound undertakings and are different from continuous operation systems. There exists a crucial knowledge gap regarding the behavior of capability traps in projects which, upon examination, could help us understand the dynamics of projects better.

This research expands the boundaries of traditional project models by identifying and explicitly modeling capability traps. A new archetypical project model was constructed by merging a simplistic project model with an archetypical capability trap model. Upon performing a univariate sensitivity analysis on the archetypical project model and the archetypical capability trap model, it was found that variables related to the allocation of resources had the most influence on continuous operations whereas variables related to the scale of resources/ effort provided had the most influence on projects.

The comparison of analyses highlighted some crucial differences between projects and continuous operations. It was found that excessive investment in capabilities can be detrimental to project progress. The study found that project teams should not sacrifice training/time and effort dedicated towards capability development when facing a strict time constraint as this would land the project in a capability trap and hurt progress in the long run. The best way for project managers to manage capability traps in construction projects would be to increase the total work effort directed towards both capability development and production activities.

DEDICATION

I would like to dedicate this study to the three most important people in my life - my mother, my father, and my brother.

ACKNOWLEDGMENTS

I would like to thank my committee chair, Dr. Ford, and my committee members, Dr. Damnjanovic, Dr. Lewis, and Dr. Wolf, for their excellent guidance and outstanding support throughout the course of this research. An extra thank you to Dr. Ford without whom this study would not have been possible.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. A special thanks to Ms. Laura Byrd for helping me manage my work and providing me with excellent advice throughout my studies at Texas A&M University.

Thanks to my parents -Dr. Vijaya and Dr. Prasanna Kumar- for their encouragement and love. They provided me with extra motivation by completing their doctorates over the course of my studies. Finally, thanks to my brother, Dr. Amit, for his patience and moral support.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Dr. David N. Ford (advisor) of the Department of Civil Engineering, Dr. Ivan Damnjanovic (committee member) of the Department of Civil Engineering and Dr. Charles Wolf (committee member) of the Department of Civil Engineering and Dr. Phil Lewis (committee member) of the Department of Construction Science.

The references used to develop background was provided in part by Dr. David N. Ford. The archetypical project model, chapter vi, was created under the guidance of Dr. David N. Ford.

All other work conducted for the thesis was completed by the author independently.

Funding Sources

This study was not supported by any external funding.

NOMENCLATURE

PMI	Project Management Institute
CII	Construction Industry Institute
NPV	Net Present Value
PMBOK	Project Management Book of Knowledge
BBW	Better Before Worse
WBB	Worse Before Better
EVM	Earned Value Management
BOTG	Behavior Over Time Graph

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

The Project Management Institute (PMI) defines a project as "a temporary endeavor undertaken to create a unique project service or result" (PMI, 2008a, p. 434). Better performance in a project makes it more likely for a project to be successful. Successful development projects are critical to success in many industries (Ford & Sterman, 1998) and construction industries are no exception. From a project manager's perspective, construction projects are considered to be successful if the team can deliver a quality product that fulfills the project scope on or under budget and on or before the scheduled deadline.

Existing literature shows us that most construction projects fail to meet the performance criteria, i.e., below budget and on schedule. A recent study performed by the Construction Industry Institute (CII) in 2015 found that only 2.5% of construction projects meet all the performance criteria. On average, 72% of construction projects are delayed with an average of 38% increase in originally contracted duration, and 63% of projects experienced cost overruns with an average of 24% increase in original contracted cost (Rivera et al., 2017). Another study reports that nine out of ten projects experience cost overrun (Flyvbjerg, 2004). Large Transport Infrastructure Projects are amongst the most controversial and are often delivered late, over budget, and providing less benefit than expected (Localetti et al., 2017). For instance, the Chanel tunnel had a cost overrun of 80% and has a negative net present value (NPV) (Aljohani et al., 2017). This project is not a standalone instance of project failure but is a rather common occurrence in megaprojects (Flyvbjerg, 2011). These megaprojects usually have the best construction crews working for them and yet they fail to meet the performance criteria.

Some of the major factors contributing to cost overrun of infrastructure projects include lack of contractor and consultant planning before the project, poor coordination, inconsistent management strategy, poor client staff communication and stakeholders' lack of participation during the conceptual phase (Allahaim & Liu, 2015). Delayed payments, financial processes, and difficulties on the part of contractors and clients, contract modification, economic problems, materials procurement, changes in drawings, staffing problems, equipment unavailability, poor supervision, construction mistakes, poor coordination on-site, changes in specifications and labor disputes and strikes were found to be the major factors contributing to schedule delays in infrastructure projects (Kaliba et al., 2009).

The Project Management Book of Knowledge (PMBOK) defines the project manager as the person assigned by the performing organization to lead the team that is responsible for achieving the project objectives. The project manager is held responsible for the successful completion of a construction project. While external factors such as large scope changes are responsible for project failure in some cases, the project manager is still accountable.

Construction projects tend to start slow and pick up pace as they go along and slow down at the end. This is because of the nature of projects; in the initial phase of a project, a significant amount of backlog is in the form of design and execution. As a result of this, a lot more resources are allocated to these processes and other activities such as quality assurance and rework has very few resources allocated to it. However, for work to be released a work package must pass through all the activities. Because of this, the work released in the start-up phase of a project is very slow. Towards the end of the project, all work exists in the form of rework and quality assurance and the progress slowing down can be attributed to the minimum duration required for the completion of these activities and errors in work hindering the project to be completed. This has been discussed later in chapter v.

Construction projects are dynamic, in the sense that the conditions of the project keep changing. Construction projects typically run into problems like equipment failure, unforeseen conditions, inclement weather, and even engineering problems. Such disturbances in a project tend to throw the project off schedule and can severely impact the project if construction teams do not have adequate capacity to deal with such unforeseen conditions. In fact, at times, these disturbances can even roll back on project progress. For instance, due to the three-mile incident, safety requirements were revised to stricter standards which severely impacted the construction progress in ongoing nuclear power plants in the United States. While rework was a major factor in the failure of the Watts Bar power plant project, taking a step back allows us to notice capability traps affecting this project.

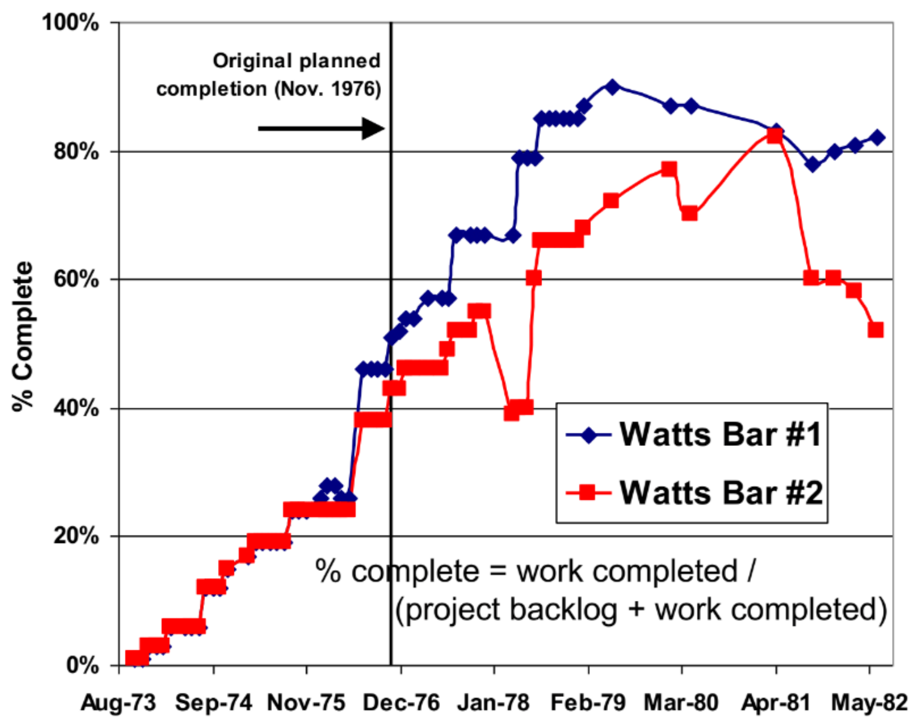


Fig 1: Watts Bar Nuclear Plant – Construction Progress, reprinted from Taylor & Ford (2008)

Oftentimes, project managers find themselves behind schedule in construction projects. This is not a favorable situation because most construction projects have strict schedules. A project manager's career is at stake in most of these cases as there is a significant amount of financial resources involved. For instance, consider a project manager with an inexperienced team tasked with a major design project is starting to fall behind schedule post 30% design submittal. What should the project manager do to regain the schedule? Project managers respond to such situations by increasing work intensity or at times by making workers cut down on their training (Li et al., 2017). This initially seems to fix the schedule delay issues and produce favorable forecasts (Li et al., 2017). Over a while workers experience fatigue, reducing the capability of project teams. As the project progresses, workers seem to get little work done and the project keeps falling further behind in terms of schedule (Li et al., 2017). This has a harsh impact on project schedule forecasts. In response to this, the project manager further directs workers to cut down on training/break time to meet the next milestone. This leads to even worse performance. The more the project manager tries to keep the crews on their grind, the worse their productivity becomes and as a result, the quality of work keeps deteriorating. It is not uncommon for project managers to work overtime. The scenario described above is an example of the behavior exhibited by a system stuck in the capability trap. Attrition of labor is another common way in which project teams lose capabilities. When workers leave a project, there is a sudden decline in the capability of the project team. This may also result in the creation of capability traps in projects.

A capability trap is a vicious cycle in which unreliable, inefficient facilities lead to high costs and a firefighting focus that prevent an organization from investing in the capabilities and programs needed to improve, thus perpetuating high costs and firefighting (Lyneis & Sterman, 2016). The theory of the capability trap recognizes that the performance of any process depends on both a set of organizational capabilities and on the intensity of work effort (Landry & Sterman, 2017). This concept has been used to study the problems faced by several organizations such as BP and DuPont (Repenning & Sterman, 2001) and public entities (Guevara et al., 2017). However, these studies have largely been limited to continuing operations whereas construction projects are discrete, time-bound undertakings.

Studies have shown that investment in increasing capability instead of increasing time spent on the production of a system can have a greater yield over a while (Repenning & Sterman, 2001). These studies indicate that managers should focus on increasing long term productivity over short term firefighting to meet everyday deadlines. While, initially, production output reduced, the long-term yield was drastically better. We identify that the capability of the project teams is something that can be controlled by project managers. Studying the capability trap in construction projects may lead to a better understanding of construction projects. Dealing with capability traps may be the key to better policy decisions and improved project performance.

Consider, as an example, an experienced project manager working on a major design project. The manager is tasked with a relatively inexperienced team of designers. The team of young engineers is very enthusiastic and is willing to work hard to get the job done. The team has a good understanding of engineering concepts and does an outstanding job of producing the preliminary design documents. The team has met every deadline to date. However, the team needs to produce detailed designs as the next set of deliverables. Detailed designs need to be constructible at project sites. This requires a deep understanding of construction activities at the site. The team, being inexperienced in construction, lacks this understanding and there is a clear capability deficit. In other words, the team is not suited to this task of developing detailed designs. The team has not worked on project sites before and as a result of this, the team is making several errors while working on detailed designs. The project is experiencing delays as a result of a significant amount of work that does not meet the quality requirements and needs to be reworked. The project manager persists with the team and chooses to make the team work for longer hours. Yet, the increased hours seem to make little difference to the progress rate. The project manager is concerned at this point because failing to finish this project effectively might harm the firm and the project manager's career. How can the project manager deliver the drawings within a reasonable amount of time? How can the project manager reduce delays in the project to get it back on schedule? (Wolf, 2020)

This study takes a system dynamics approach to investigate capability traps in construction projects. The study will consider the existing models of capability trap and construction projects and attempt to integrate them. The integrated model will help us identify the effect of capability traps on construction projects and study the difference in the impact of capability traps on construction projects in comparison with continuous operations.

CHAPTER II

BACKGROUND & PROBLEM DEFINITION

What is a capability trap? How does it work?

A capability trap is a vicious cycle in which unreliable, inefficient facilities lead to high costs and a firefighting focus that prevent an organization from investing in the capabilities and programs needed to improve, thus perpetuating high costs and firefighting (Lyneis & Sterman, 2016). The theory of the capability trap recognizes that the performance of any process depends on both, a set of organizational capabilities and on the total amount of work effort (Landry & Sterman, 2017). Capabilities include the productivity and quality of the plant, equipment, technology, physical tools, and the knowledge and skills of the people who work in the system (Landry & Sterman, 2017).

When firms face pressure to deliver higher output, they can do so by increasing the total amount of work effort by increasing work intensity, longer hours and cutting corners in the process. These solutions produce immediate results and help resolve existing issues in the short run. However, these often come at the expense of less time scheduled for training, maintenance and other activities designed to develop capabilities (Repenning & Sterman, 2001). The productivity of work activities is a function of capabilities possessed by the firm. For instance, if a team has a set of engineers trained in computer design, they will be able to work on the design process at a much faster rate than a team of engineers who are not familiar with computer design. Over a period of time, workers begin to forget essential knowledge and skills which have not been employed regularly and also, as new technologies develop, older methods become obsolete. Knowledge obsolescence occurs very slowly in some parts of construction and faster in others. For instance, framing techniques for concrete pouring has remained similar over a significant period and hence, exhibits a very slow rate of knowledge obsolescence whereas, surveying tools, cloud-based project management and designing process have seen several innovations and continues to develop actively. Hence, these activities are subject to a faster rate of knowledge obsolescence. As a result of these events, the capabilities of a firm decrease over a while causing the productivity of work effort put in by the labor to decline as well. However, there is a significant delay between these two events whereas, the increase in work output happens as soon as the work effort is increased. This leads managers to believe that increasing work effort at the expense of efforts devoted to capability development will lead to better results. When the productivity of the workforce drops after a significant delay resulting in an output shortfall, the managers – based on their previous experience, are biased to cut further capability development effort in favor of production effort. This worsens the situation and puts the organization deeper into the capability trap.

Development of Capability Trap

The theory of the capability trap can be traced back to Jay Forrester's concept of "shifting the burden to the intervener", this was first observed while describing Urban Dynamics (Foresster,1971). Sterman & Repenning (2001) further developed this idea and used the term capability trap to describe this phenomenon. The theory of capability trap was first used by Sterman & Repenning to describe why the operations of manufacturing and tech firms were failing despite the firms minimizing their downtime. This gave rise to a simple but effective archetype (Fig 2) which has been used multiple times to describe capability traps across various industries.

Assume a firm producing at a rate equal to the desired output at initial conditions. As capabilities erode, the total capabilities of a firm decline causing the performance of workers to decline. This decline in performance results in a performance shortfall. The manager may opt to cover the short-term gap by shifting his resources from improvement effort to work effort. This leads to a sudden boost in performance and cuts down the performance shortfall. However, as capabilities continue to erode the performance deteriorates further and the manager has to shift more resources to work effort from improvement effort. This forms a balancing feedback loop that drains the capability out of the system, this loop is referred to as the work harder loop (Fig 2). The output of a system in work harder loop displays a better before worse behavior mode. The manager may opt for working smarter rather than working harder but opting to shift resources. Since labor is pulled out from the production effort, initially the output declines further and increases the output shortfall. However, over a period of time, the investment in improvement effort works well and results in capability growth. An increase in capability increases the productivity of workers and enhances the overall performance resulting in decreased performance shortfall. This forms a balancing feedback loop which increases the capability of the system, this loop is referred to as the work smarter loop (Fig 2). The output of a system in work smarter loop displays a worse before better behavior mode. Investment in improvement effort or work effort occurs at the expense of the other type of effort, this is because time is a constrained resource. By investing in work harder loop, the system is headed for ruin and investment in improvement effort results in a sustainable increase in performance. This is represented by the reinvestment or ruin feedback loop which is reinforcing in nature.

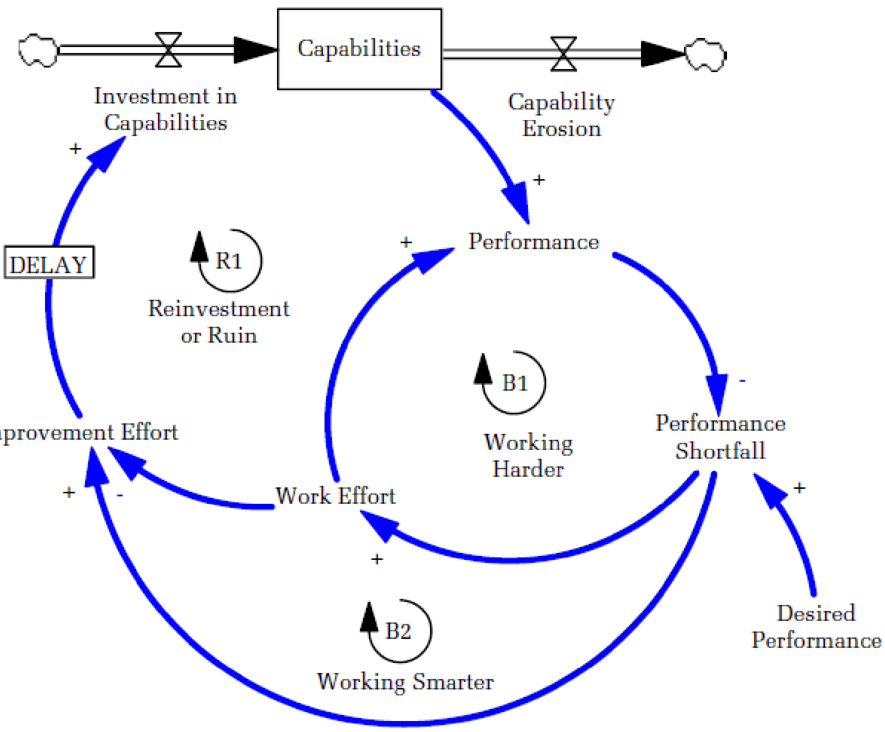


Fig 2: Capability Trap, reprinted from Repenning & Sterman (2002)

While in theory, working smarter is the obvious choice it may not be the best option for the manager to take in practical situations. In practice, managers are under constant stress to meet the deadlines failing which they might be subject to losing their standing with the firm and might even be fired. Under such high-pressure conditions, managers are far more likely to pick the work harder path to decrease the output shortfall. Since this happens at the expense of investment in improvement effort, it leads to a decline in capabilities and loss of performance. Loss of performance results in a performance shortfall and the manager is once again at risk of losing his position. This forms a vicious cycle where the capability of the system keeps eroding leading to worse performance each time. Because of the competitive nature of markets, managers often get trapped in such situations.

Under the context of continuous operating systems, the theory of capability traps has been studied in detail and we now have a much better understanding of such continuous operating systems. In particular, research on this tends to focus on what leads to a capability trap, how to avoid such a trap, how to manage such a situation and the biases involved while dealing with capability traps. Gonçalves (2011) describes how a lack of resource oftentimes leads to a firm to be stuck in a capability trap. Rahmandad (2012) explores how firms have a bias towards investing in operational capabilities to enhance short term performance over long term dynamic capabilities because it provides a competitive advantage. Repenning & Sterman (2001) demonstrate how attribution errors lead to bias towards favoring the work harder loop (Fig 2). Recent studies focus on escaping capability traps; Andrews et al., (2012) explains initiatives that fail and suggests an alternative approach called problem-driven iterative adoption (PIDA) to overcome capability traps. Morrison (2012) explores project improvement dynamics under constrained resources and suggests that additional capabilities can serve as a slack, especially when working under resource constraints.

Today, capability traps have been identified to exist in a wide array of technical and non-technical systems (Landry & Sterman, 2017). For example, the highways in the United States have been deteriorating at an alarming rate and increased government funding has not seemed to solve this issue (Guevara, et al., 2017). This was because while resources were limited, they had to choose between reconstruction and maintenance at the same time. In a second case, Universities, despite having long term horizons and enormous amounts of endowment, fail to implement more win-win programs, i.e. programs with both social and economic benefits, as a result of capability traps leading to failure of previous attempts at such programs (Lyneis & Sterman, 2016). Capability traps exist in human systems too: abused children in foster care, bridge collapses and the ever-rising costs of healthcare in the United States can be attributed to capability traps (Landry

& Sterman, 2017). Capability traps have even been used to study how to bring down greenhouse gases and promote sustainability (Sterman, 2015).

Studying capability traps in systems help us comprehend the system better, which in turn allows us to make better policy decisions. For instance, in a study conducted at Texas A&M University, researchers found that leveraging the savings obtained by conserving energy to fund green initiatives not only saves more energy but also drives down costs when compared to other alternatives (Faghihi et al., 2014).

Consider a project manager working on a large project with a relatively small portion of the construction crew specializing in steelwork. The project manager realizes that the crew does not have enough capacity to deliver finished steel reinforcement in time for the project to proceed as planned. To ensure that the reinforcement reaches concrete crew in time, the project manager can either make the steel crew work harder by increasing the working hours and intensity of work effort. This does increase the production rate of reinforcement, but the increase is marginal, and the work produced may be subject to more rework. This is because crews are prone to make more errors when working at a greater intensity over long periods of time. The project manager can also address this issue by sending his crew to trade school to train in bar bending and tying steel. This action is along the lines of working smarter. Initially, the rate of production of steel reinforcements decreases as the workers take time away from work to train but once they return from training sessions, they deliver reinforcement at a faster rate.

Knowledge Gap - Capability traps in project models and why it is important

Existing literature on capability traps focuses on continuous operations across a wide range of industries. As discussed in the previous section, the theory of capability trap can be used to successfully explain the failure mode in operations. However, this has not been studied under the context of discrete time-bound undertakings such as construction projects. The progression of a project can be broken down into three phases; the start-up phase, the middle phase- where a significant portion of work gets released, and the closeout phase. When project progress is tracked, it can be observed that the work released in the startup phase and closeout phase are nonlinear, whereas the work released in between these two phases can be approximated to a straight line with a positive slope. Startup and closeout phases do not exist in continuous operations. Continuous operations operate in a state of equilibrium for the most part whereas projects cause a system to transition from one state of equilibrium to another.

More often than not construction projects fail to meet the schedule deadlines, a study shows that about 72% of all projects worldwide fail to meet the deadlines with about a 38% increase in project duration beyond the stipulated deadlines (Rivera et al., 2017). When delays creep into a project, project managers are forced to increase the work effort to catch up with the deadlines which increases the errors. Such errors could put the project further behind schedule. This is one example of what typically occurs in a construction project and it exhibits symptoms of a capability trap.

Existing literature on project failures study various attributes such as rework, tipping points, wastage, resource management, etc. However, there have not been studies to emphasize the impact of capability traps in construction projects. While project managers have cited teams lacking the capability to get the work done as a reason for project failure, this has remained uninvestigated. If we can examine and document the effects of capability trap on construction projects, it may help future project managers avoid capability traps. Capability traps identify the lack of capability as the root cause of project delays and this, if proven accurate, can change the way projects are managed.

Literature review on relevant project models

For this research, the study on project models shall be limited to the versions of dynamic project models that take feedback mechanisms into account. The project model shall not take factors such as ripple effect and knock-on effects into consideration. This is because the study is intended to develop an understanding of the effects of capability trap alone on construction projects. Using an elaborate project model would increase the likelihood of the capability trap interacting with other model elements and make it harder to identify the effect of capability trap.

Lyneis & Ford (2007) provide a detailed history of the development of project models in their work titled "System dynamics applied to project management: a survey, assessment, and directions for future research". While project models have been around for a long time, the first model to describe developmental projects in terms of value-adding aging chains was proposed by Ford & Sterman (1998). The Ford & Sterman (1998) model effectively describes how the work flows through a project (Fig 3). A major assumption made while developing this model was that the total project was broken down into fungible work packages. This assumption has been key to developing project models as it allows the modeler to neglect the differences in durations of various activities hence making it easier to analyze the project.

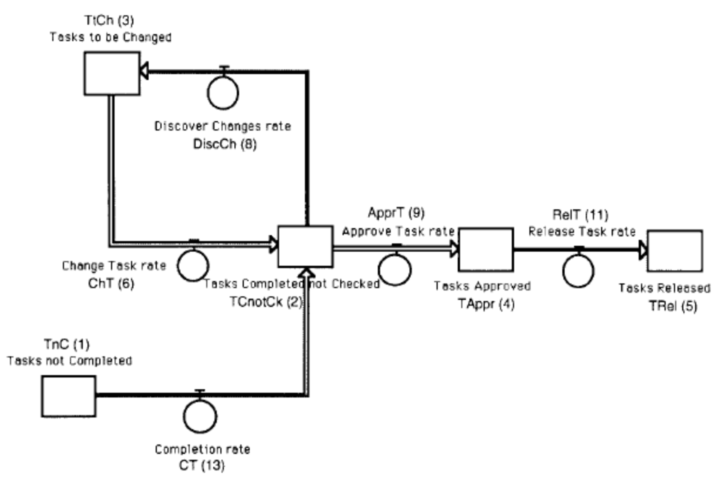


Fig 3: Project Management model – reprinted from Ford & Sterman (1998)

Project models developed intended to capture and describe various phenomenon typical to project behavior have been an extension of the Ford & Sterman (1998) model. The project model proposed by Ford & Sterman (1998) has further developed and has been used to study the 90% syndrome where projects appear to have slowed down progress during its end phase (Ford & Sterman, 2003), strategic management of complex projects (Lyneis et al., 2001), tipping point failure (Taylor & Ford, 2006), Management of tipping point dynamics (Taylor & Ford, 2008) and even to develop project control models (Lyneis et al., 2007). This model has been used to study specific cases such as failure of Limerick nuclear power plant (Taylor & Ford, 2006) as well as entire systems such as highway projects (Ford et al., 2004). Prominent firms such as BP, Bath, Ford, Hughes/Raytheon, and the World Bank use these flight simulators for training purposes (Lyneis & Ford, 2007).

For this research, a variant of the tipping point project model (Taylor & Ford, 2006) has been used. This variant only models the rework and resource management in a project. This was done to help study the effects of capability traps without additional disturbances. This model shall be further discussed in chapter v.

Problem definition

A typical project manager practitioner's problem was discussed in the introduction. The project is behind schedule and the project manager has assessed that the team cannot get work completed on time if they kept working similarly. So, the project manager increases the work effort by putting in longer work hours, diverting all resources towards production activities and increasing the work intensity by demanding more from the project team. This, in theory, should make up for the lack of capabilities. However, the project manager notices that the work is not progressing as intended, so there must be something that the project manager has not considered.

We hypothesize that the capability of the project team is continuously eroding as the resources allotted to capability development has been allotted elsewhere.

Assuming that the capability of project teams as constant is not realistic. Equipment breakdowns occur regularly on a project site and even the productivity of team members has been observed to vary greatly throughout a project. Previous studies have demonstrated that productivity in a project team varies based on the policy decisions employed by the project manager (Bernardini et al, 2018). By assuming that the capability of the project team to be a constant and forcing the project team to work harder, the project manager might be leading the team deeper into the capability trap. However, the project manager could assume that the loss of capability is very marginal to affect the project significantly. The project manager would want to finish the project on schedule as the consequences of not doing so could be severe. The project manager would have two significant questions - How can the project manager produce the deliverables within a reasonable amount of time? How can the project manager reduce delays in the project to get it back on schedule? (Wolf, 2020)

While project managers have experienced the existence of capability traps in construction projects, few project managers are aware of its mechanism and how to overcome such situations. Incorporating a capability trap archetype should help us study the behavior of construction projects under the effects of capability trap archetype. This could potentially help project managers perform better on their projects. Building a capability trap archetype on to a project model should help us compare the effect of capability trap on construction projects with that of continuous operations.

Construction projects are discrete time-bound undertakings and operations are only carried out when the system is not in equilibrium. They are measured differently than continuous operations such as car manufacturing or oil production. If the project manager is stuck in a capability trap, any information on capability traps would be invaluable. Significant research has been conducted on understanding capability traps. However, these studies alone would not prove of much value to the project manager because the theory of capability trap has only been explored in continuous operations and not construction projects. Therefore, a significant question we try to answer in this study is how does a capability trap affect a project differently than a continuous operation? Additionally, if the project manager were to tackle the situation effectively, they should learn how to get the most from their actions. What points or activities in new the system can they change to get the best results?

This study will answer the following primary research questions to help project management practitioners:

- **How would a capability trap affect a discrete project differently than continuous operations?**
- **What are the high leverage points in this new project model which considers capability traps?**
- **Are principles applied to manage capability traps in continuous operations systems effective in managing capability traps in construction projects?**

CHAPTER III

RESEARCH METHODOLOGY

As indicated in the problem definition, this study is aimed at implementing and analyzing capability traps in construction projects. To accomplish this, this study will first explore the existing capability trap archetypical model and analyze it. Using this capability trap archetype, a new archetypical project model to which capability trap has been added will be constructed and validated. The study will use a univariate sensitivity analysis to compare the existing archetypical capability trap model with the archetypical project capability trap model to identify similarities and differences between the two models.

Due to the dynamic nature of construction projects, this study will use system dynamic models to capture the effects of feedbacks. The data used to calibrate the new project capability trap model was compiled from existing models. Since the project model and the capability trap model do not have a common performance measure, a new performance measure will be developed; this is discussed in chapter vi. The models used and developed for this study will be created using Vensim PLE, a simulation software.

To answer the research questions posed earlier in chapter ii, the following research methodology will be implemented:

- Perform a literature review and study the archetypal capability trap model (Repenning & Sterman, 2002) and project model (Ford & Taylor, 2006).
- Reconstruct both the archetypical capability trap model and the project model to make them suitable for this study.

- The capability trap archetype will be integrated with the project model to construct a new project model with a capability trap.
- Validate the new project model using standard tests (Sterman (2000)) to ensure that the model is reasonable.
- Subject the new project capability trap model and the archetypical project model to univariate sensitivity analysis to determine high leverage parameters in both systems.
- Use the results of the analysis to answer the research questions posed in chapter ii.

CHAPTER IV

CAPABILITY TRAP MODEL

Given that the background of the capability trap model has already been established in chapter ii, we shall explore the mechanics of the capability trap archetypical model in this chapter. We shall also examine the assumptions made while developing the archetype.

For this study, we examined a well-established capability trap archetypical model published by Lyneis & Sterman (2016). The model defines capabilities as assets that build up as the result of investment and erode over time as equipment ages, employees leave, knowledge becomes obsolete, etc. While this model was published along with a paper explaining the root cause of building maintenance issues at a reputed university and proposal of measures to counter the situation (Lyneis & Sterman, 2016), it was determined that this could be applied to other studies concerning capability traps. This capability trap model is based on systems in continuous operations. As the published model had a few hidden elements, the capability trap archetypical model was reconstructed based on the equations obtained from the original model. That model will be referred to as the archetypical capability trap model or the model.

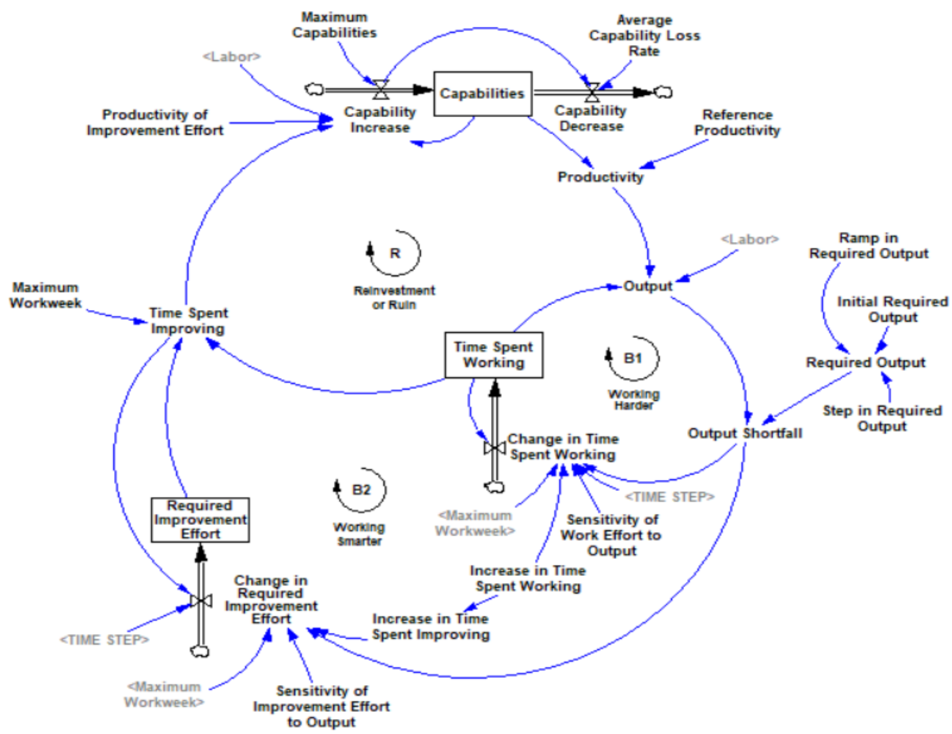


Fig 4: Capability Trap, reprinted from Lyneis & Sterman (2016)

This model structure describes the effect of capability on output (Fig 4). The output is controlled by the productivity of workers, time spent working and the total number of workers. Productivity is defined as a function of capability as shown in the model. If the required output is greater than the produced output, it generates an output shortfall. To overcome the shortfall, the manager can either increase the time spent working or increase the time spent improving. Time spent working can be improved by making the work effort of the model more sensitive to output shortfall or increasing the time spent working. Both of these actions come at the expense of time spent improving and while it covers the output shortfall initially, the output shortfall worsens as the capability erodes over a period of time. This mechanism forms the work harder loop. The manager may also decide to bring the shortfall down by investing in improvement efforts. Time spent improving can be increased by making the improvement effort of the model more sensitive to output shortfall or by decreasing the time spent working. This results in an immediate fall in output thus worsening the output shortfall. However, over a period of time, the investment in improvement efforts increase capability and thus boost productivity. This results in an increase in output and covers output shortfall. This mechanism forms the work smarter loop. Investment in improvement effort and investment in work effort occur at the expense of each other, either actions have an impact on capability. Should the manager choose to work harder, the capabilities erode, and should the manger choose to work smarter the capabilities grow. This forms a reinforcing loop called the reinvestment (in capability) or ruin loop.

The model assumes that every worker devotes a certain portion of work towards production and the remainder of the workweek towards improvement activities, this can be controlled by adjusting the reference fraction of effort to output. This is a realistic assumption; the manager can control the resources and total effort towards certain activities. When the system faces an output shortfall, the manager realizes that the system is operating under suboptimal conditions and the system is failing to meet the demand of consumers. To increase the output, the manager should increase either the productivity or the labor or the time spent working or a combination of these.

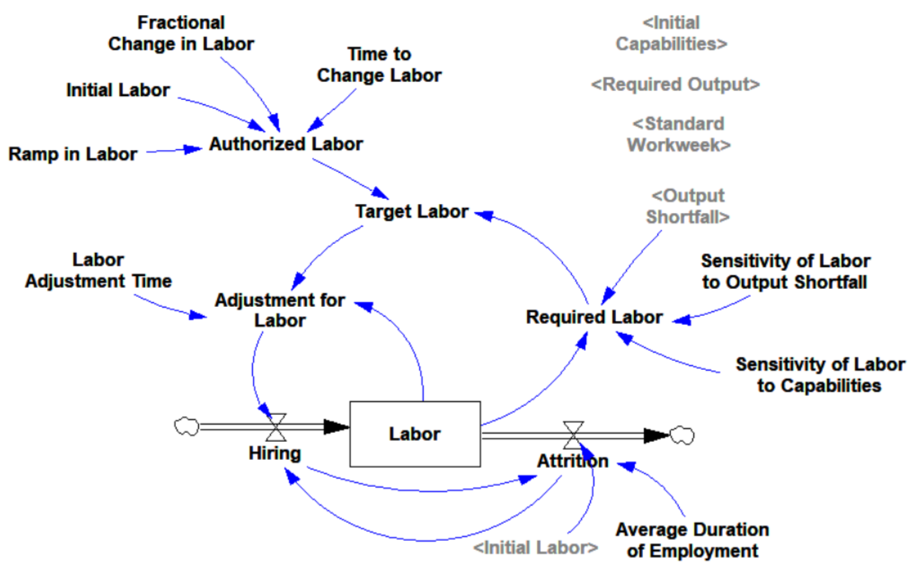


Fig 5: Workforce Dynamics, reprinted from Lyneis & Sterman (2016)

The model also describes the labor dynamics in continuous operations (Fig 5). The total size of the workforce is controlled by hiring and attrition rates. The model hires at a rate equal to the sum of attrition rate and adjustment for labor to reach target labor. The workers are assumed to leave the team after 2 years. Initially, the model assumes the size of the workforce to be 100 people. Target labor is defined as the minimum of authorized labor and required labor. As target labor increases or decreases, the model adjusts the total size of the workforce accordingly within the labor adjustment time (0.25 year). Authorized labor is exogenously modeled and the base case values of parameters controlling authorized labor are set such that the authorized labor is equal to 100 people. The values of ramp or step increase in labor authorization are set to 0 for base case conditions. Required labor is defined as the size of the workforce required to produce at a rate equal to the required output. Required labor increases as output shortfall increases. Initially, the sensitivity parameters linked to required labor are set to 0.

The model is formulated such that it starts in a state of equilibrium. In other words, the model assumes that for any given initial value of state variables, i.e., initial capabilities, reference productivity, reference fraction of effort to output and labor, the output produced by the system is equal to the required output and the capability of the system remains constant. The output of the system does not react to changes in labor or productivity unless there is an output shortfall, i.e., the required output is greater than the output being produced. This makes sense because managers avoid overproduction. Further analysis of the model was made under the condition of the existing output shortfall.

Consider the case where the manager decides to increase the total effort by increasing the time spent working. This action would lead to an immediate improvement in output and decrease the output shortfall. However, because time is a constrained resource, an increase in time spent working occurs at an expense of time spent improving. Time spent improving is defined as the minimum value among the required improvement effort and the difference between the length of workweek and time spent working. When the manager increases the time spent working, it leads to a decrease in time spent improving. As time spent improving decreases, the magnitude of the inflow driving capability decreases. This leads to a decrease in capability, driving the productivity downward. As productivity decreases, the output decreases and gives rise to a significantly larger output shortfall. If left unchecked, the output shortfall increases over subsequent periods. This demonstrates a better before worse (BBW) behavior in output as shown in the figure below (fig 6).

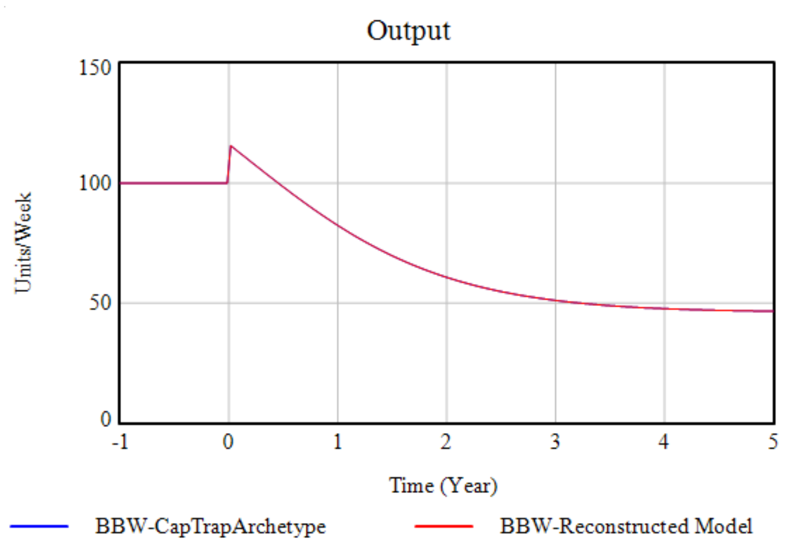


Fig 6: Better Before Worse

Consider a second case where the project manager decides to act oppositely to the first case and decreases the time spent working in favor of time spent improving. This leads to an immediate decline in output and increases the output shortfall. However, as the time spent improving increases, the inflow to capability increases more rapidly than the outflow resulting in a net increase in capabilities. This increases the productivity of the team and results in a greater output as shown in the figure below (fig 7). This mechanism serves to reduce output shortfall.

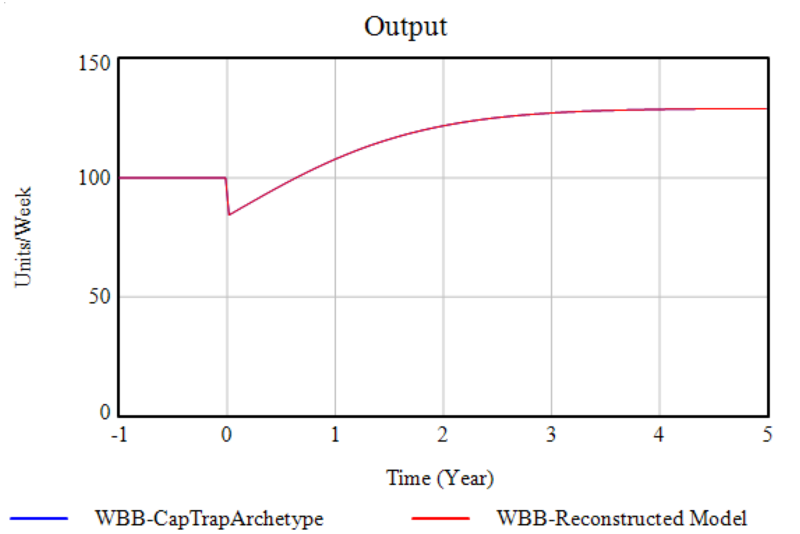


Fig 7: Worse Before Better

The manager may decide to increase the number of workers while keeping the production and improvement hours constant. The archetypical capability trap model has a labor adjustment modeled into it as shown above (Fig 5). The model adjusts labor (total workforce) towards "Target Labor". Target labor is defined as the minimum of required labor and authorized labor. A manager may not hire labor if they have not been authorized to do so even if there is a clear requirement of labor. Assuming that the manager has been authorized to hire additional labor if there is a requirement of additional labor, the manager will bring in additional workers. This will increase the output significantly as shown in the figure 8. However, managers do not often employ such measures because it is not cost-effective.

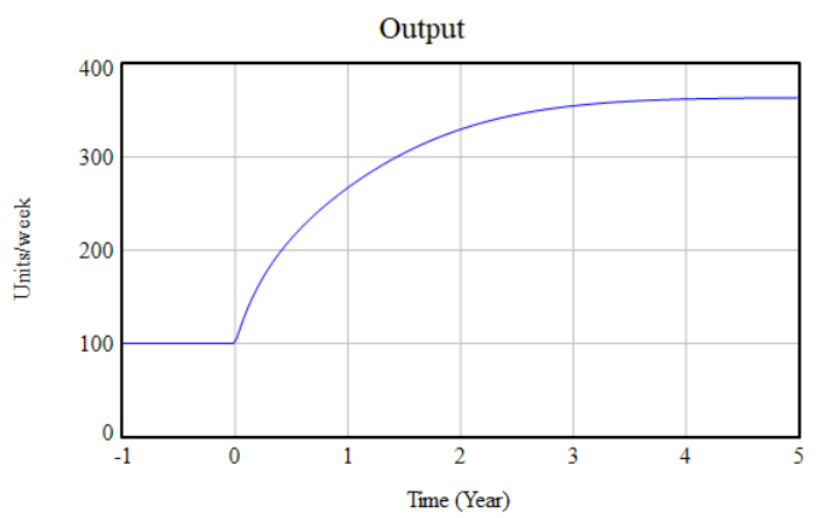


Fig 8: Impact of additional labor on output

A copy of the archetypical capability trap model developed by John Sterman was obtained from http://jsterman.scripts.mit.edu/Online_Publications.html#HowToSave. This model was observed to have hidden elements. To gain a better understanding of this model, it was recreated using the equations of the archetypical project model downloaded from the source mentioned above. The recreated model was validated against the archetypical capability trap model developed by Sterman. The details of this recreated capability trap archetypal model are provided in Appendix A.

Since the archetypical project model has been designed to start at equilibrium, the model produces output at a rate equal to the required output in most instances. This does not provide useful results when the model is subject to sensitivity analysis. To overcome this issue, a new base case was designed by exogenously introducing an output shortfall. This was accomplished by setting the value of the required output ramp to 50 units/week. The model was analyzed for the new base case. The results of the sensitivity analysis obtained by using this new base case were compared with the results of the sensitivity analysis performed on the project capability trap model (Chapter vii – Analysis & Results).

CHAPTER V

PROJECT MODEL

As stated previously, the study on project models shall be limited to the versions of dynamic project models that take feedback mechanisms into account. While several project models have been developed to study and explain various observations and practices such as earned value management (EVM), ripple effect, tipping point, etc., the project model shall not consider these factors. This is because- the study is intended to develop an understanding of the effects of capability trap alone on construction projects. Using an elaborate project model would increase the likelihood of the capability trap interacting with other model elements and make it harder to identify the effect of capability trap. Therefore, the current research used a very basic project model with only rework and workforce distribution developed by Ford and Sterman (1998).

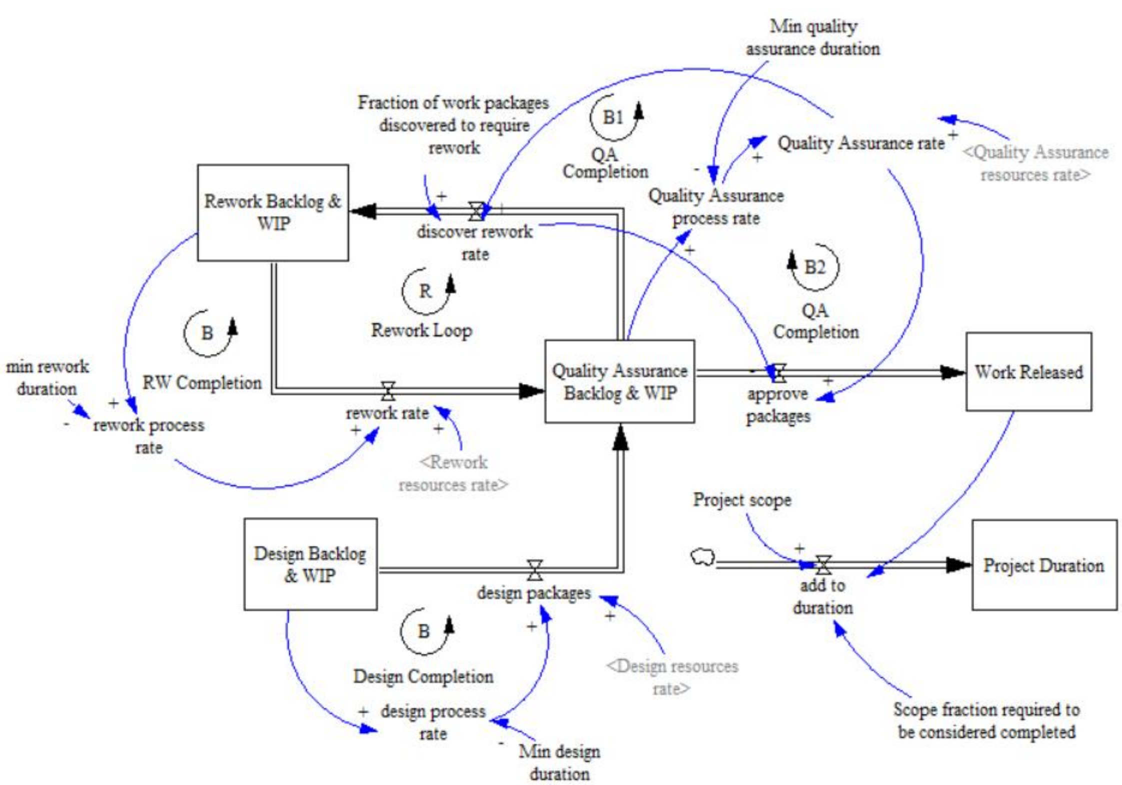


Fig 9: Project Model – Workflows, based on Taylor & Ford (2006)

The version of the project model chosen for this study was taken from Taylor & Ford (2006). Elements such as knock-on effects, ripple effects, etc. were removed from this model to make it suitable for this study. This model assumes that the workforce for a given project is constant and the productivity of work processes is also a constant. This model has two parts; the first part demonstrates the flow of work through the project (fig 9). This model assumes that the entire scope of work can be broken down into smaller fungible work packages. The rate at which work progresses from one backlog to another is constrained by two factors, the process rate, and the resource rate. The process rate is defined as the ratio of work backlog to the minimum process duration. The work packages are either found to be defective and need rework or they are approved by the quality assessment engineers. The rework engineers then work on the defective package and send it back to the quality assessment team. Should the work package meet the required quality, the quality assessment engineers release the work package or, in other words, mark it as complete. For a project to be considered complete, the ratio of work released to the project scope should be equal to the "scope fraction required to be considered complete". The performance of the project, in this model, is measured using project duration. However, to compare performance with the new project, this is not a suitable measure. To compare project progress with the progress of continuous operations, the middle phase of the project can be used to measure steady-state progress rate which is comparable to the output in the archetypical capability trap project model. The development of this new performance measure is discussed in chapter vi.

The second part of the model describes resource allocation in a project (Fig 10). This model assumes that the total workforce for the project remains constant. The model distributes the number of workers assigned to a specific task based on the backlog. For instance, during the starting phase of the project, all the packages are yet to be designed and, hence, the model would distribute the entire workforce to the design team. The distribution of the workforce is assumed to be linear, the desired number of workers for a particular activity is defined as the fraction of backlog present in that activity times the total workforce. The actual number of employees working on any particular task is adjusted based on the desired number of employees for that specific task. The productivity of workers is assumed to be constant. The resource rate of a given task is defined as the number of people working on that specific task times the productivity of the workers. In other words, the resource rate is equivalent to the total work effort.

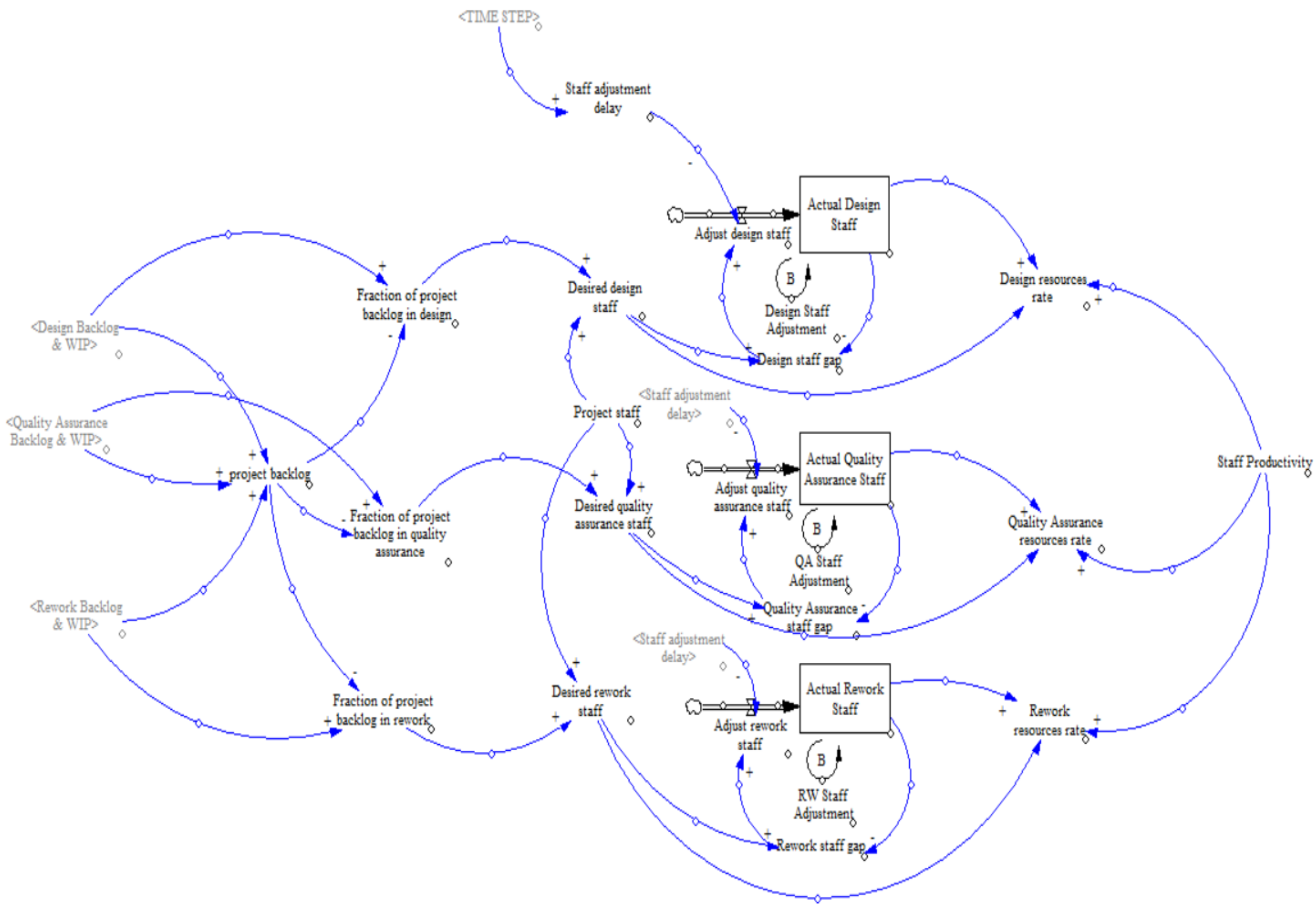


Fig 10: Project Model – Workforce Distribution, based on Taylor & Ford (2006)

This project model is simple and is capable of producing the s-shaped curve expected in construction projects (Fig 11). Project system dynamic models have been significant in the construction industry and helped understand and realize several concepts in construction projects. For instance, project models have allowed us to study tipping points in detail, and by using detailed project models we can predict and avoid such crucial events in construction projects. Project models have also been used to study the effects of various policy decisions on projects without the project manager having to implement such policies. This gives crucial foresight and helps project managers make better policy decisions and effectively manage project teams.

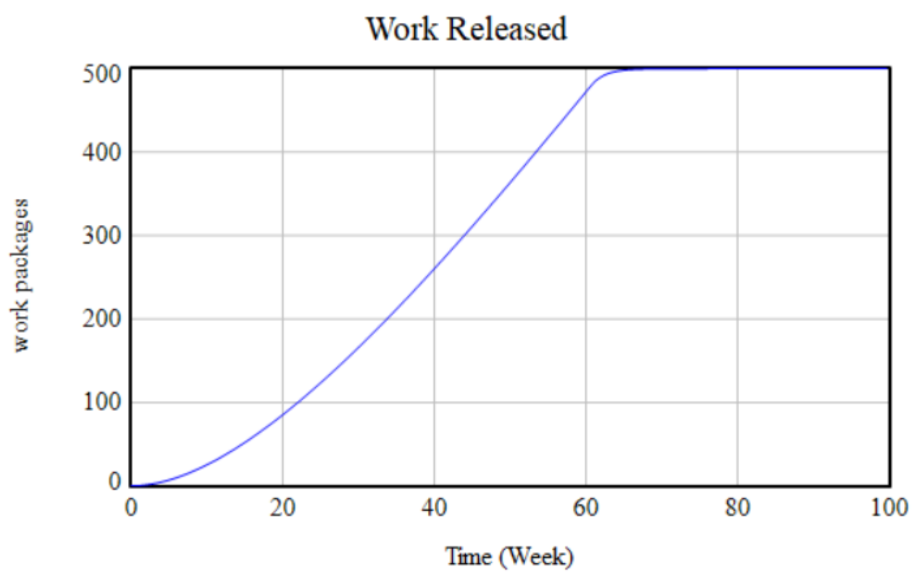


Fig 11: S-shaped curve, work released

Unlike the capability trap archetypical model, the project model accounts for the work progressing through the system. We shall use this project model as the base over which the capability trap archetype shall be built. While the project model uses a different performance measure compared to the capability trap model, we believe it is possible to compare the performance of the two models. This will be explored further in chapter vii.

CHAPTER VI

PROJECT MODEL WITH CAPABILITY TRAP

Introduction

To study the capability traps phenomenon in construction projects, a capability traps layer based on the capability traps archetype described in chapter iv is added on to the project model described in chapter v. Only changes to the model described in Chapter v are described here. Both of these models make several assumptions that must be considered before integrating the two models. The project model has an aging chain describing workflow and we shall use this structure in the new model. The proposed model, keeping in line with the project model, assumes the total project scope to be constant. The project model assumes a constant workforce, whereas the capability trap model considers the workforce to be a parameter that may vary over the course of a simulation. For this model, we shall assume the total workforce at any point throughout the project to be constant.

The project model described in chapter v considers only production activities (design, quality assessment & rework). However, the proposed project model with the capability trap shall consider both production activities and capability development activities. The project model distributes the total workforce to the production activities based on the work backlog in each of those activities. Also, the new model assumes that a fraction of the total workforce is allotted to capability development activities and the remaining workforce is allotted to the three production activities based on the size of backlogs. The project model assumes the error detection fraction to be constant throughout the project lifecycle. However, the new project capability trap model considers it a function of capability and therefore, the error fraction is modeled endogenously.

While the initial error fraction based on the previous project model is considered as a reference, the error fraction in this model decreases as the capability deficit decreases and sensitivity of the rework to capabilities increases. The project model assumes that the minimum process durations of production activities to be constant, whereas, the new model considers the possibility of change in minimum process durations. This change in minimum process durations is subject to variation in capability deficit fraction, reference minimum duration of process and sensitivity of process duration to capability deficit. If the value of the sensitivity parameter is above zero, the minimum process duration decreases as capability deficit fraction decreases.

The archetypical capability trap model assumes that capability directly affects productivity. However, this does not explicitly explain the role of capability development in a construction project. Upon a closer examination, it was observed that increased capability in construction projects had two major impacts. Primarily, it resulted in higher quality work, in other words, the rework fraction dropped. Secondarily, the work took a less time i.e., reduced duration of production activities. The proposed model will model the role of capability development in projects explicitly. The archetypical model assumes that every worker is subject to certain hours of capacity development activities in a workweek. This might not hold in construction project teams where personnel is subject to training as and when certain skills need to be developed to complete tasks. Therefore, we consider that only a fraction of the workforce to indulge in capability development activities. In the case this fraction is set to 1, i.e., the entire workforce is set to capability development, the progress rate goes down to zero (Appendix C).

The archetypical capability trap model considers the reference productivity of workers to be variable whereas, the project model discussed in chapter v defines it to be constant. Since it is proposed to define and model the effect of capability improvements explicitly; to keep the structure of the project capability trap model similar to the archetypical project model wherever possible, the productivity of production activities and capability development activities are modeled as constants. Working smarter increases productivity indirectly – by reducing the error fraction and by reducing the minimum time taken to complete a production activity.

Model & Calibration

The proposed model comprises of three main structures, the workflow portion, the capability trap portion, and the resource allocation portion. While this proposed model consists of all the elements used to build up the project model discussed in chapter v, a few elements have been modified in some capacity as described below.

Figure 12 depicts the workflow and how various process rates are affected by capability. This portion of the model is similar to the workflow model structure described in chapter v except for the addition of the capability trap layer.

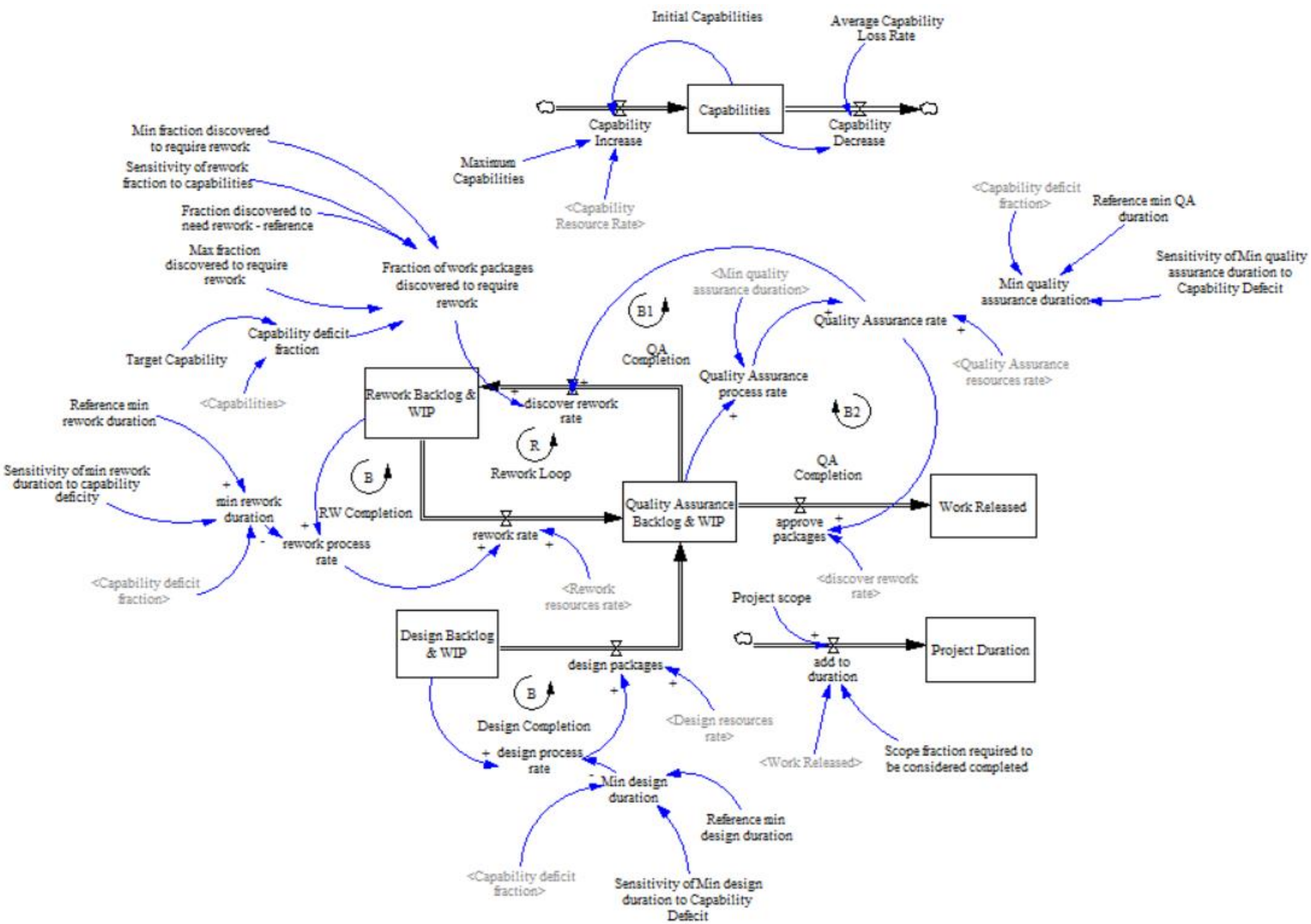


Fig 12: Workflow and Capability Structure

Figure 12 also represents the capability trap layer added on to the basic project structure. The capability trap portion of the revised project model is based upon, and closely resembles, the capability trap portion of the archetypical capability trap model described in Chapter iv. The capability of the system increases based on the capability resource rate and the scope for capability improvement. The capability resource rate represents the total amount of work effort towards capability development and the productivity of the work effort combined. For this research, capability is assumed to erode at a constant rate as defined by the average capability loss rate. Initial capability represents the actual capability of the project team at the start of the project. The project manager generally has an idea of what resources are needed to complete a project. Target capability is defined as the capability required to complete the project. The difference between the current level of capabilities and the target capabilities gives us the capability deficit, or the number of capabilities required to complete the project as planned if provided throughout the project. The capability deficit fraction is defined as the ratio of capability deficit to target capabilities.

The values for all capability parameters have been recalibrated for this study. The target capabilities and initial capabilities have been set to 100 for the base case. The maximum level of capabilities has been set as 1000 for this model. The average capability loss rate has been set as 1/104 per week for the base case, this is based on the same value used in the archetypical capability trap model when converted from yearly scale to a weekly scale.

As described previously, this model considers the effect of capability on project progress in detail. As the capabilities of a project team improve, the quality of work produced is higher resulting in rework fraction reducing significantly. The rework fraction has been limited to a minimum value of zero, which represents the extreme case where all work is correct and approved, and a maximum value of one, which represents the extreme case where all work is flawed gets rejected by the QA team. At the beginning of a simulation, a reference value of rework fraction based on the project model (chapter v) is considered. The base value of this reference variable is 0.2. The equations for the rework fraction are built such that as the capability deficit fraction increases, the rework fraction increases, and vice versa. The model also considers a sensitivity parameter which is a measure of the volatility of rework fraction to change in capability deficit fraction. This is an exogenous parameter whose base value is assumed to be equal to one.

The other effect of improvement in capabilities is a reduction in time of production activities. The rate of production activities is constrained by either the amount of effort and productivity of effort or the minimum time to complete the activity. By improving the capability of production teams, it is possible to reduce the minimum duration required to complete an activity. When the simulation starts, the model considers a reference value for the minimum duration of an activity. This reference value is set as 10 weeks.

The minimum process duration to complete an activity varies in accordance with the capability deficit fraction. As capability deficit fraction increases, the minimum duration required to complete an activity increases and vice versa. This has been modeled such that the least possible value of minimum activity duration is 1 week. The model also considers a sensitivity parameter which is a measure of the amount of response of minimum process duration to change in capability deficit fraction. This is an exogenous parameter whose base value is assumed to be equal to one. The same structure has been used for all production activities.

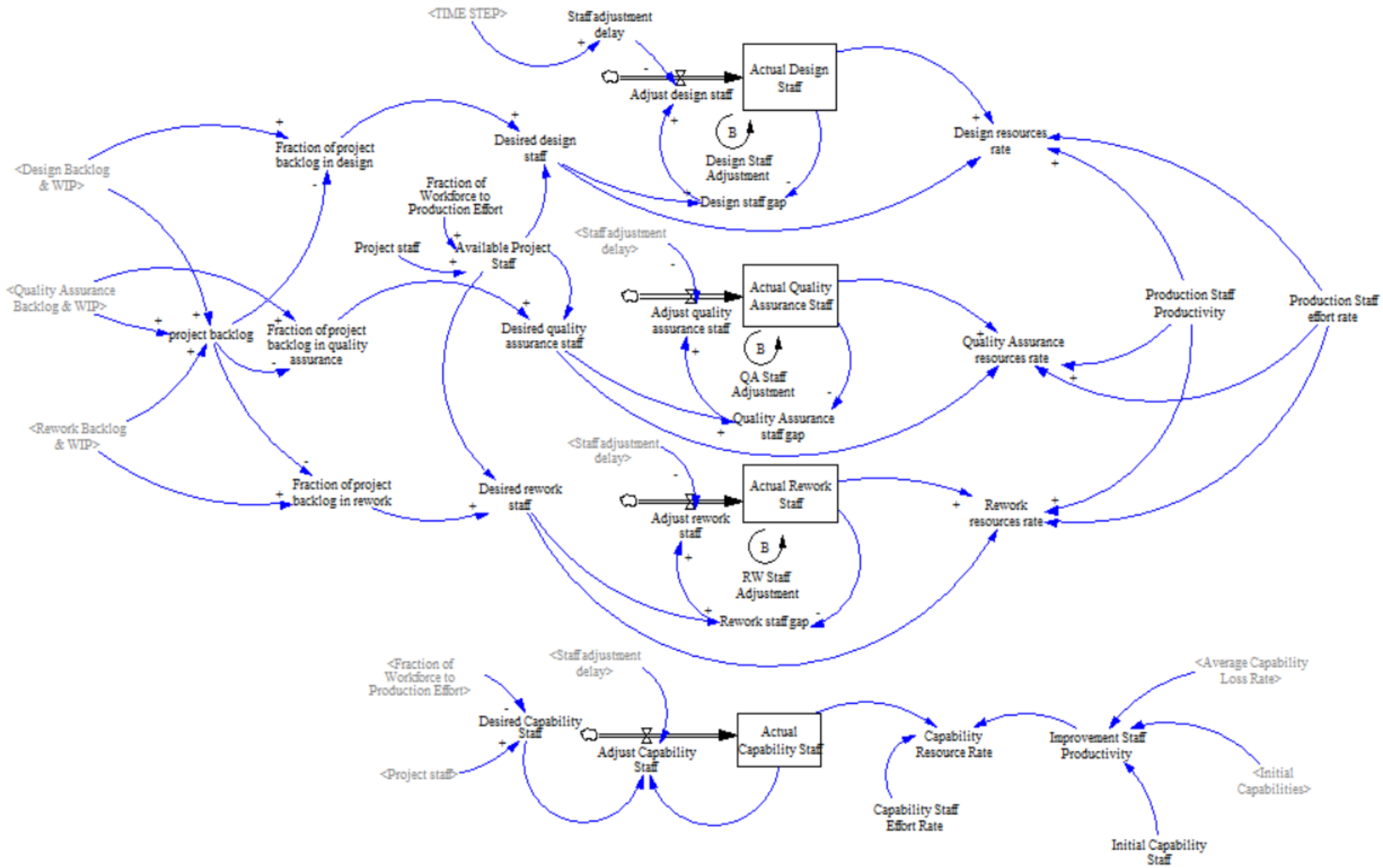


Fig 13: Resource Allocation Structure

Figure 13 represents the resource allocation structure. This is very similar in structure to the resource allocation model used in the project model save for a few minor differences. However, these differences may have a significant impact. The project model discussed in chapter v only considered production activities (initial design, QA, and rework). This model considers capability development activities in addition to production activities. The model still calculates the desired staff for a production activity based on the size of the backlog. However, the total project staff is not available to be allocated to production activities because only a fraction of total staff is sanctioned to production activities, in the base case this fraction is set at $0.9\overline{4}$, and the remainder of the staff is allotted to capability development activities. The fraction of total staff allotted to production activities was found to be $0.9\overline{4}$ after the model was calibrated such that capabilities stock remains at a state of equilibrium if all other exogenous parameters are set to base case conditions. The project manager usually similarly allocates human resources. Based on the available staff and size of work backlogs, the model distributes the staff to various production activities. Production staff effort rate is defined as the total effort put in by the employees over a workweek. This parameter is set as 1 week per week (1 workweek is roughly equal to 40 hours/week). The resource rate for production activity is defined as the product of effort rate times the productivity of effort and the production staff allocated to that activity. The resource rate captures the number of work packages the team can process if it is constrained by resources.

As mentioned previously, a portion of total staff is allocated to capability development activities. Since the project manager decides how to manage work effort, the fraction of employees allocated to capability development is modeled as an exogenous variable. Capability staff effort rate, similar to the production staff effort rate, is defined as the total effort put in by the employees over a workweek. The base value of this parameter is set to 1 week per week. The productivity of improvement effort is the capabilities developed per person per week. The productivity of improvement effort is set such that the model starts in equilibrium. The model also considers the initial value of capability staff to be equal to 1. These conditions were employed to make sure that the proposed project model starts in a similar condition to that of the archetypical capability trap model (chapter iv). The capability resource rate captures the total effort put towards capability development.

As seen in Fig 13, the project capability trap model models allocation of labor for production activities as a first-order delay. Based on available labor and the fraction of labor in given production activity, the desired staff is calculated. Depending on the difference between the desired staff and the existing level of staff, the actual staff is adjusted to meet the desired levels after a staff adjustment delay. This delay is also used to model the adjustment of capability staff. While this delay exists in project models, it does not exist in the archetypical capability trap model where the distribution of effort towards production and improvement occurs instantaneously. In the project capability trap model, the staff adjustment delay is set to be equal to the time step. It is necessary to make this delay insignificant so that the performance of the new model may be compared with the capability trap archetypical model.

Performance Measure

The project model considers the performance of one project and the capability trap model considers operations of facilities where several products are produced. The project model (chapter v) uses project duration as the performance measure whereas the archetypical capability trap model measures performance as output in terms of units produced per week. This makes it hard to equate and compare the performance of the two models. To compare the proposed model with the capability trap model, it is imperative to find a common performance measure.

Fig 14: BOTG of Work Released, Project Model

Consider the s-shaped work released curve produced by the project model as described in chapter v. The graph can be divided into three sections as shown (Fig 14). Part 1 represents the startup phase of the project and is shaped like the exponential growth curve. Part 2 of the curve represents the middle phase in a project and the curve almost represents a linear growth. While part 2 is not linear, the curvature is sufficiently minimal for it to be considered linear for all practical purposes. Part 3 of the curve represents the closeout phase and represents goal-seeking behavior. If the output in the capability trap model is measured in cumulative terms by using a stock, it would closely represent a behavior similar to part 2 of the curve shown above. Since the middle phase in a project shows similar behavior to continuous operations, we shall call this as continuous operations phase or steady-state and make use of this property to build a performance measure for the proposed model.

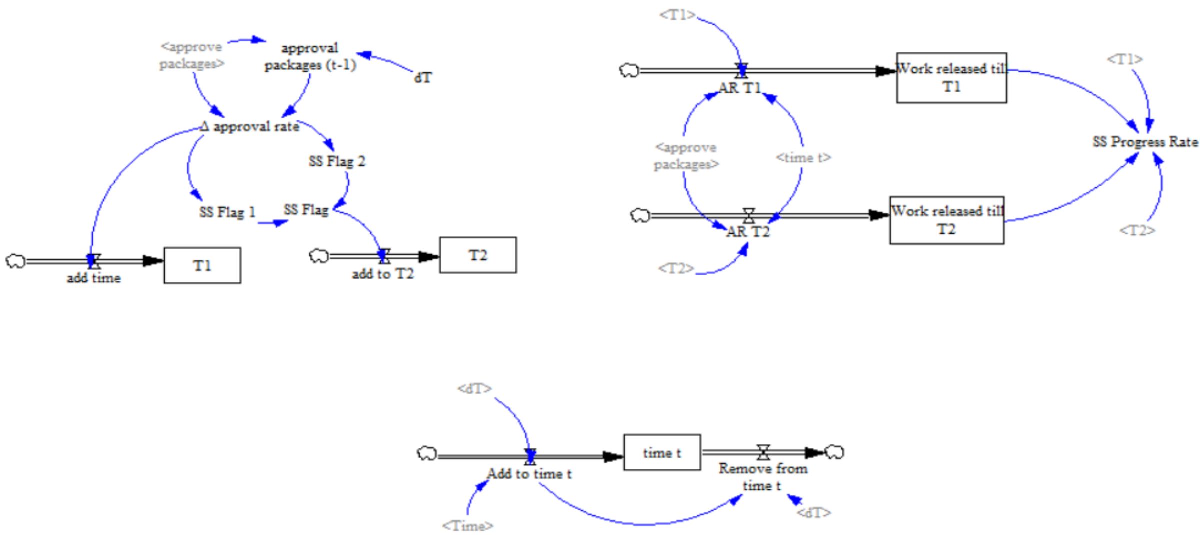


Fig 15: Performance Measure

The slope of part 2 (Fig 14) should be equal to the work packages produced every week. This is equivalent to the performance measure used in the archetypical capability trap model. To capture the slope of the middle section of the S-shaped curve, we require four pieces of information, i.e., time at the start and end of part 2 of the curve, and work released at the beginning and end of part 2. To capture these pieces of information, we added additional structure to the model (Fig 15).

We measured the difference in approval rates, approve packages and approve packages (t-1), with a time gap (dT) of 1 week to obtain Δ approval rates. By overlapping this curve with the work released curve (Fig 16), we were able to determine that the work released curve displayed a stable growth behavior when the change in approval rate roughly lay between 0.4 to 0 and negative infinity to -0.2, i.e., $(-\infty,-0.2)\cup(0,0.4)$ for most cases. However, by considering this interval, we introduce a small discontinuity when the change in approval rate transitions from a positive to a negative value. To account for this discontinuity, a small value of time was added to time T_2 while calculating work released and subsequently, the slope of part 2 of the graph. These observations hold even when the model is not simulated under base case conditions. Using the calibrated values and flag functions the values of time T_1- time at the end of part 1/start of part 2 of the graph, and T_2- time at end of part 2 of the graph, was captured. During the univariate sensitivity analysis, it was found that these calibrated values did not apply to all cases. In cases, where the calibrated values were found to be invalid, the values used in flag functions were modified accordingly by overlaying curves of Δ approval rates and work released and observing the starting and ending points of the middle phase of the project where the output was roughly linear. Using values on the Δ approval rates for flag functions proved to be effective in capturing the values of T_1 and T_2.

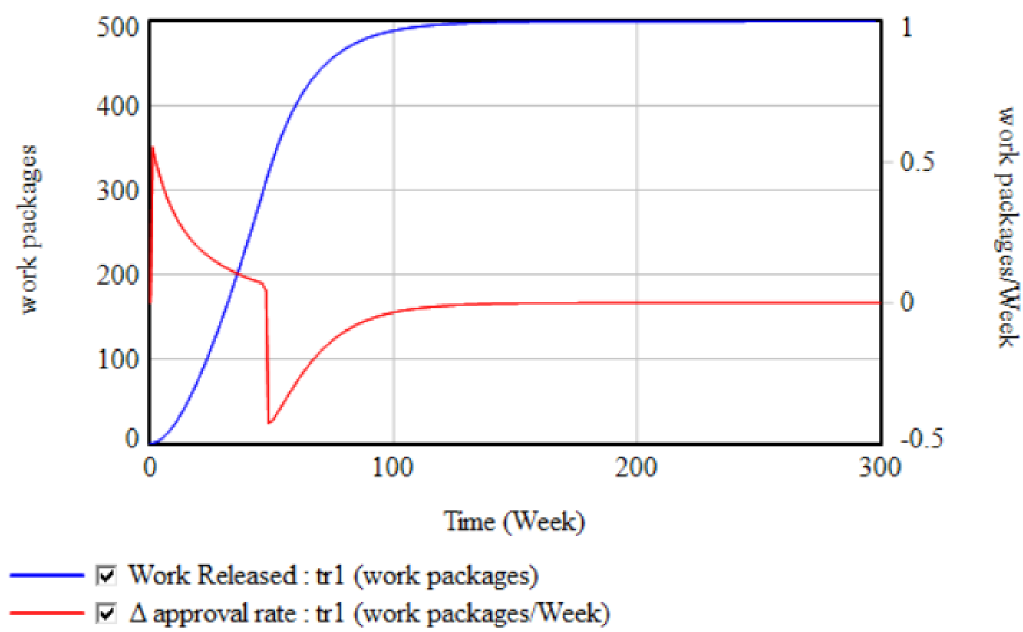


Fig 16: Work Released & change in approval rate

The next piece of information required to calculate the slope of part 2 of the curve (Fig 14) is work released at the end of part 1 (W_1) and work released at the end of part 2 of the curve (W_2). Since time T_1 & T_2 were captured as stocks, simulation time, time t, was also modeled as a stock. Work released was tallied up till the absolute value of the difference between time t and T_1/T_2 was less than 1 and by using this technique, it was possible to capture the values of W_1 & W_2. The steady-state progress rate can be defined as the ratio of the difference between W_2 and W_1 to the difference between T_2 and T_1.

Typical Behavior

The proposed model has been validated as a part of this study (appendix C). The model validation file is a comprehensive document. This section explains a few typical behaviors. The new model can produce outputs similar to the behavior modes displayed by both the capability trap archetypal model and the project model.

Fig 17: BOTG work released over time, PM with Cap Trap

Figure 17 demonstrates that the new project model with the capability trap is capable of producing an S-shaped output curve similar to the project model (chapter v). This could easily be achieved by turning off all the sensitivity parameters by setting them to zero and changing the value of Fraction of Workforce to Production Effort to from 0.94 to 1. In this case, the capability of the project team declined as there was no effort invested in capability development. However, as the model was made insensitive to capability it did not have any impact on project performance. Such a situation is not realistic.

The model was simulated five times- under base case conditions, under a work harder condition where the Fraction of Workforce to Production Effort was set to 0.98, a work harder only condition where the entire workforce was distributed towards production activities and a work smarter condition where the Fraction of Workforce to Production Effort (FWPE) was set at 0.80, and a work smarter condition where excessive resources were devoted to improvement effort by setting the Fraction of Workforce to Production Effort to 0.20. The value of Fraction of Workforce to Production Effort was the only difference between these five simulations. The project scope was set to 1000, this change helps us capture the difference in the behavior of these five conditions better.

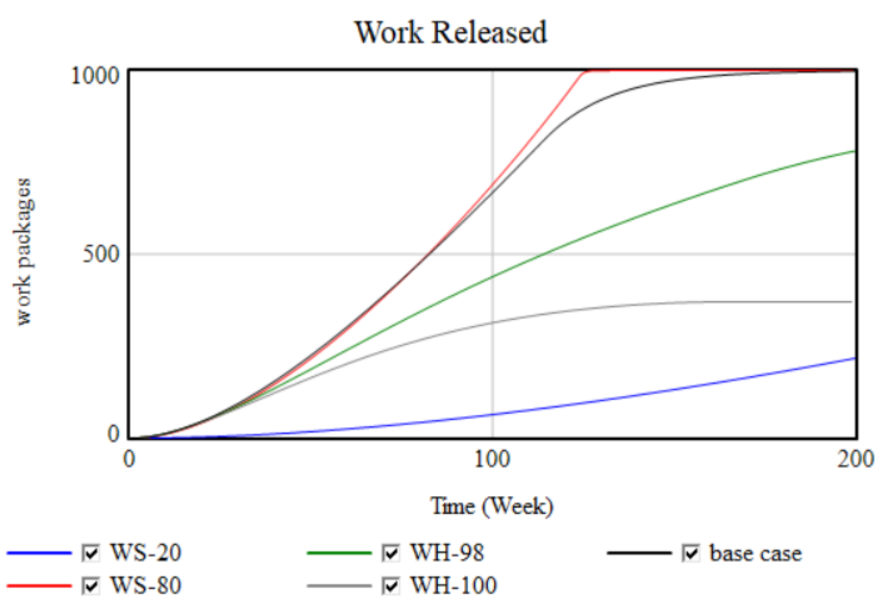


Fig 18: BOTG work released, PC model

When we examine the behavior over time graphs of these five simulations, we can observe that the work smarter curve with FWPE set to 0.8 completes the work quicker than base case conditions whereas both work harder condition requires longer to complete the project than base case conditions and have failed to complete the project within the stipulated time (Fig 18). However, when the fraction of the workforce to production effort was set to 0.2 representing an extreme case of work smarter the system produced the poor performance which was worse than the performance when the model was set to work harder only although its trajectory is improving at the end of the simulation. This occurs because of the insufficient workforce put towards production activities.

A closer look at the same graph (as seen in Fig 19) reveals that in initial stages work harder conditions were more successful in releasing work quicker than base case conditions and work smarter conditions were releasing less work than base case conditions.

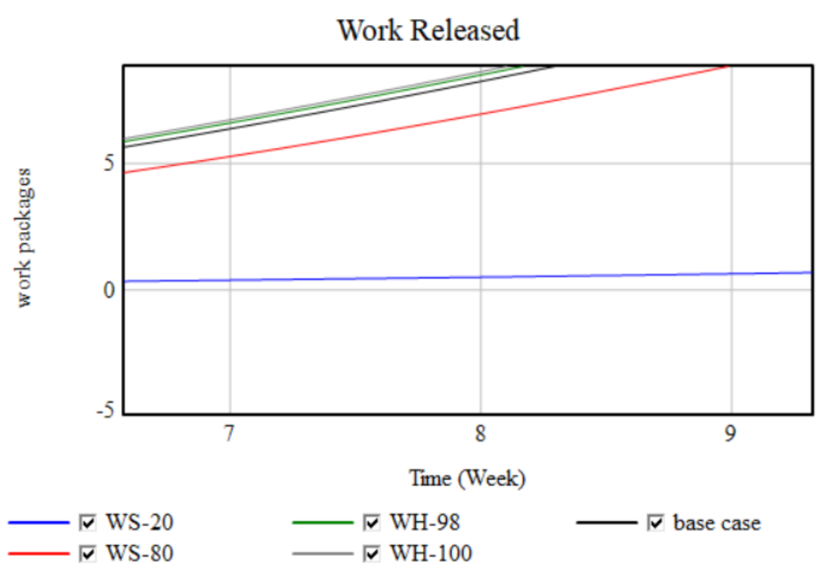


Fig 19: A closer look of BOTG work released, PC model

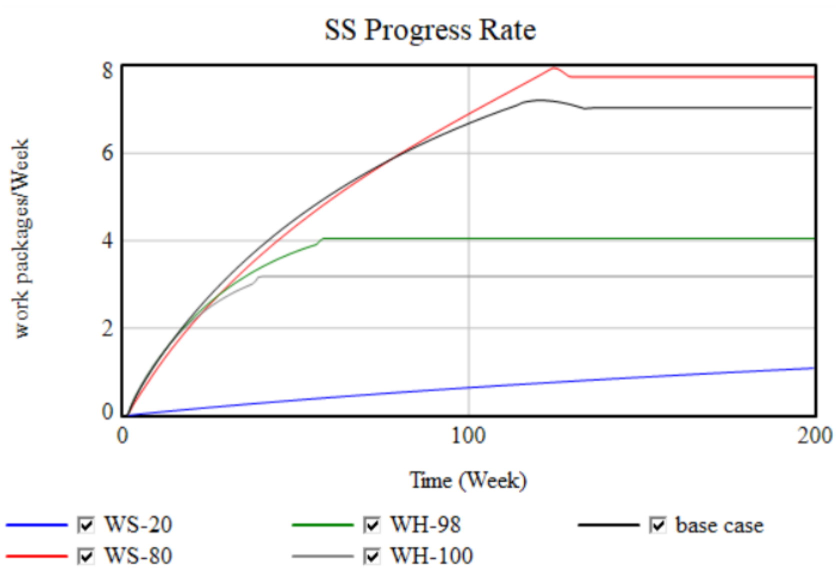


Fig 20: Steady-State Progress rate, PC Model

From figure 20, we can observe that working smarter had a significantly higher steady-state progress rate when compared to working harder conditions. Figure 21 shows us that the model is calibrated such that the capabilities are constant under base case conditions. Additionally, Figure 21 depicts the capability growth under working smarter conditions and capability erosion under working harder conditions.

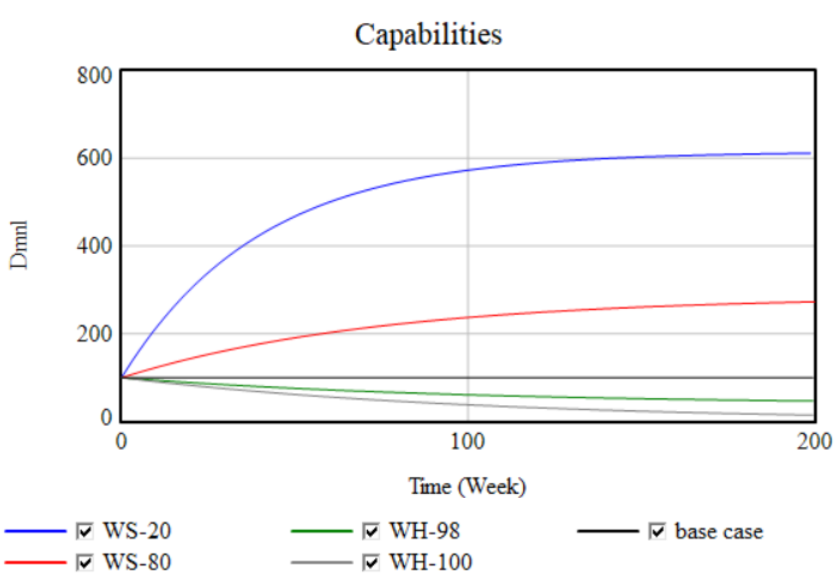


Fig 21: Capabilities, PC Model

The output of the project capability trap model cannot be directly compared with that of capability trap archetypical model. This is because the steady-state progress rate in the project capability trap model is used to capture output per week as a snapshot once the project has reached the closeout phase, the output in archetypical project model captures the behavior over time of output. To prove that the new project model behaves similarly to the capability trap archetype, a case was considered where the entire workforce is initially set to production activities, however, at around week 100, the project manager realizes that the progress rate is slowing down due to loss of capability. The project manager then allocates about 20 % of the workforce towards capability development. Fig 22 captures the behavior over time of work released. Fig 23 compares the approval rate of this case against the work harder only case. A close observation of Fig 23 reveals a dip in approval rate as the system switches from work harder to work smarter. At this time the work released also slows down as observed in Fig 22. From this graphical evidence, it can be observed that the model produces a worse before better behavior under work smarter conditions and a better before worse behavior under work harder conditions.

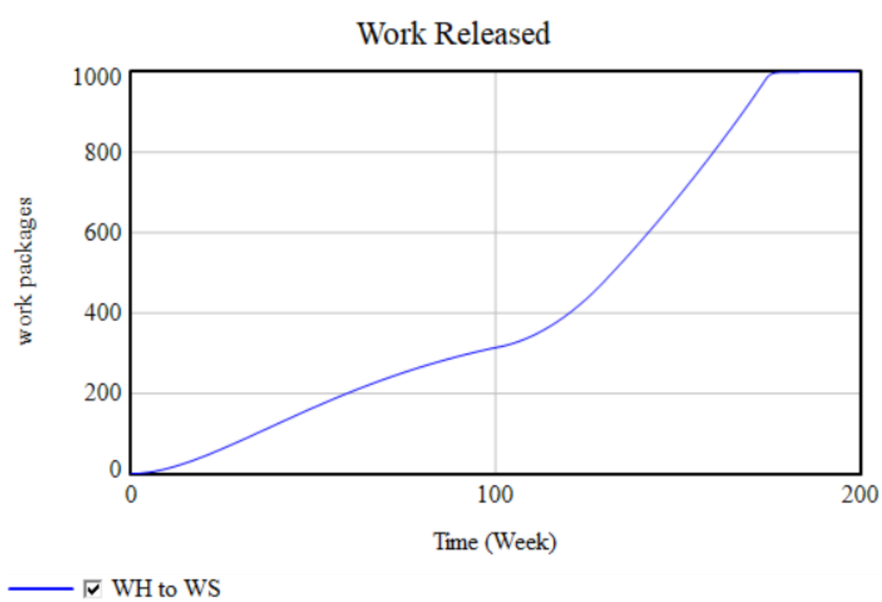


Fig 22: BOTG Work released – work harder to work smarter switch, PC Model

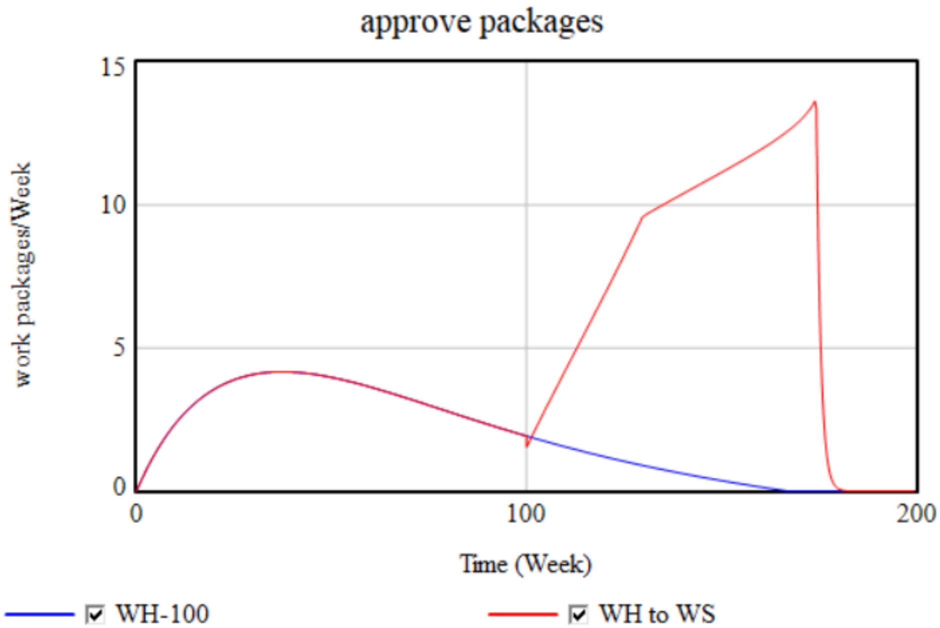


Fig 23: BOTG Approval rate – WH only and WH to WS switch cases, PC Model

CHAPTER VII

ANALYSIS & RESULTS

General Notes

The central premise of this study was defined in chapter ii- how does capability trap affect projects? And how do capability traps affect projects differently than continuous operations? After integrating the capability archetype on to project model, we now proceed to answer these questions by analyzing the new project model and comparing the results of the analysis with an analysis performed on the archetypical capability traps model. A simple but effective way of comparing the effect of capability trap in these two distinct situations is by performing univariate sensitivity analysis on both models.

For this test, the output in terms of units produced per week was chosen as the performance parameter in both models. However, since the project model was calibrated to work with a significantly smaller output, the test was measured as a ratio between the output at a given input to the output at the base case in terms of percentage. Furthermore, since the output of the archetypical capability trap model was a hundred for the base case values of the input, no such adjustment was necessary.

Capability Trap Archetypical Model

To understand the parameters which had a high impact on the capability trap archetypical model, a univariate sensitivity analysis was performed. Fig 24 represents the aggregate of the cases described below. To ensure that the results of sensitivity analysis of both models are comparable, this analysis was performed under the condition of constant workforce size.

It was found that the archetypical capability trap model would not be reactive to changes in input parameters unless an output shortfall was introduced, i.e., it would produce the same output in almost all cases. To induce an output shortfall, a ramp of 50 units was introduced from time 0 to 5 years in the required output. Figure 24 depicts the graph of univariate sensitivity analysis as performed on the archetypical capability trap model.

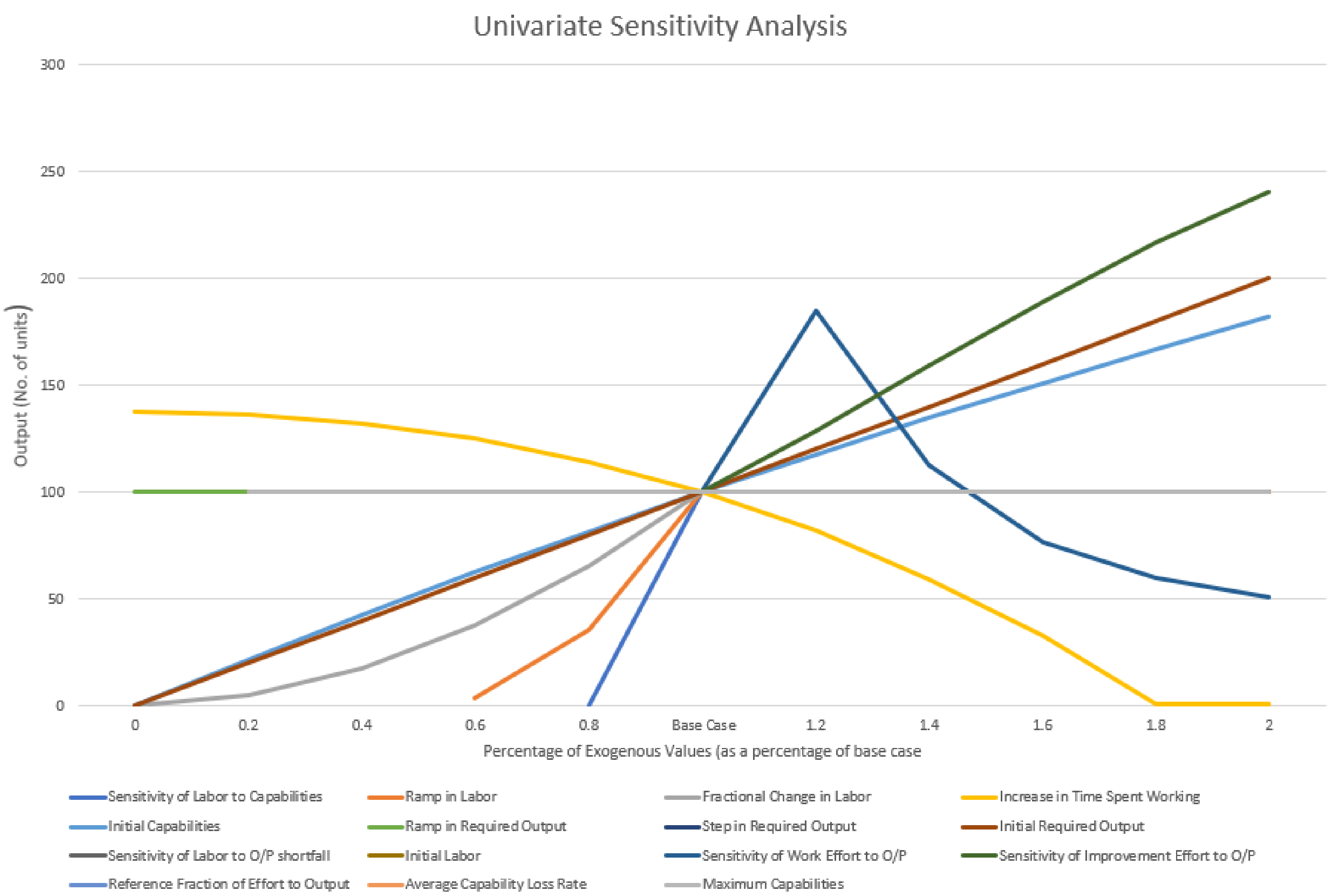


Fig 24: Univariate Sensitivity Analysis – Capability Trap Archetypical Model

Case 1: Increase in Time Spent Working

This exogenous parameter does not represent overtime as the name suggests. This model assumes that the time employees work every week is constant, but the time spent between improvement activities and time spent on work can vary.

An increase in time spent working happens at the expense of the time allotted for improvement activities such as training programs.

As we increase the time spent working, we decrease the investment in capability activities and as a result, the capability reduces over time resulting in a massive reduction in output. The converse is also true, decreasing the value of this parameter increases the output over a period of time (Fig 25).

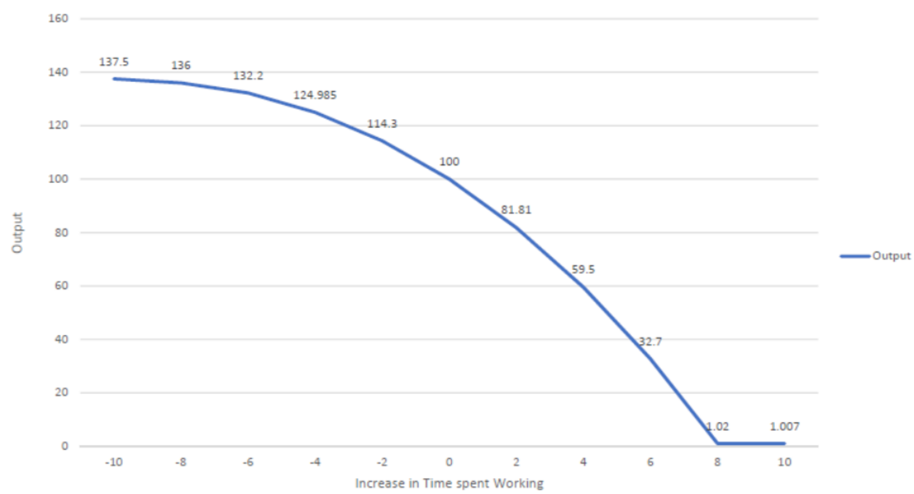


Fig 25: Increase in Time Spent Working vs. Output at the end of the simulation

However, this only represents the output at the end of the simulation. An increase in the time spent working does increase the output initially as shown in the following figure obtained by increasing the time spent working by five hours. The red line in figure 26 below demonstrates better before worse behavior

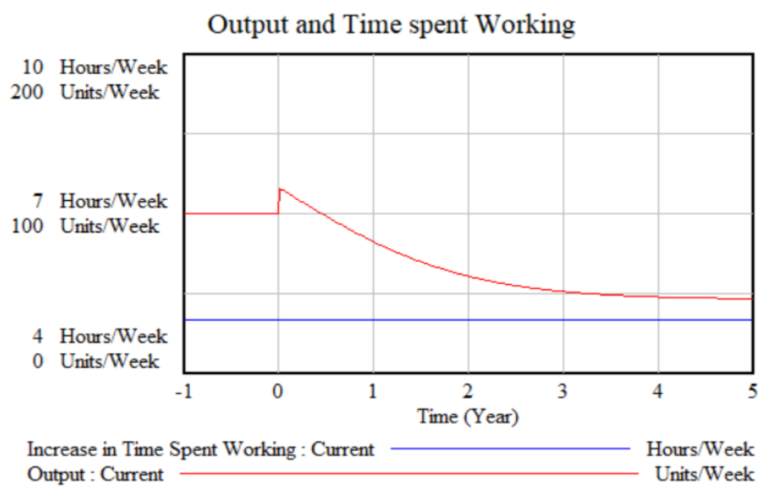


Fig 26: Output vs. Time – better before worse

Upon decreasing the value of Time spent working, we can observe a sharp dip in output followed by a substantial increase over time. The red line in figure 27 below demonstrates worse before better behavior. Figures 26 & 27 demonstrate the fundamental behavior of the capability trap archetypical model.

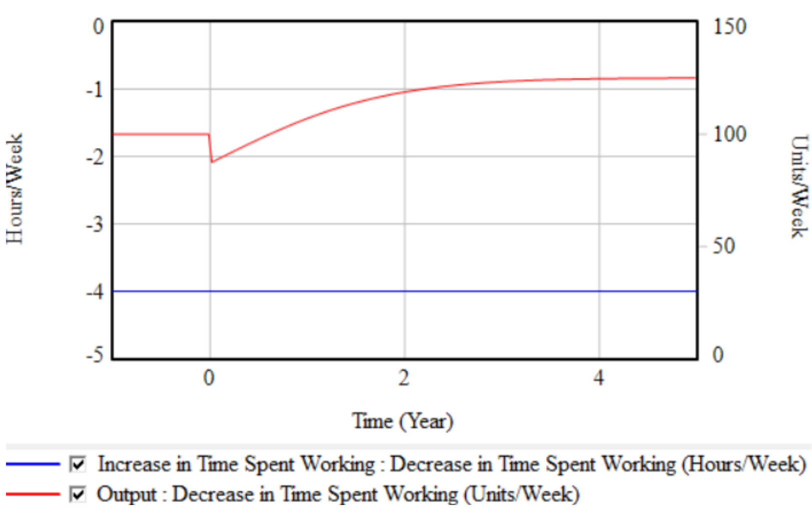


Fig 27: Output vs. Time – worse before better

Case 2: Initial Capabilities

Increasing initial capabilities increases the output and decreasing the value of initial capabilities decreases the output (Fig 28). As initial capabilities increase, the value of capability stock at time t=0 increases, as capabilities increase, the output increases too. However, increasing initial capabilities increases the value of productivity of improvement effort resulting in an increase in the value of the inflow "capability increase" which in turn increases the capabilities. The second mechanism has a profound impact on output. This is in alignment with the general understanding that increasing capability yields better output and vice versa. Here, the base case value of the initial simulation is 1.

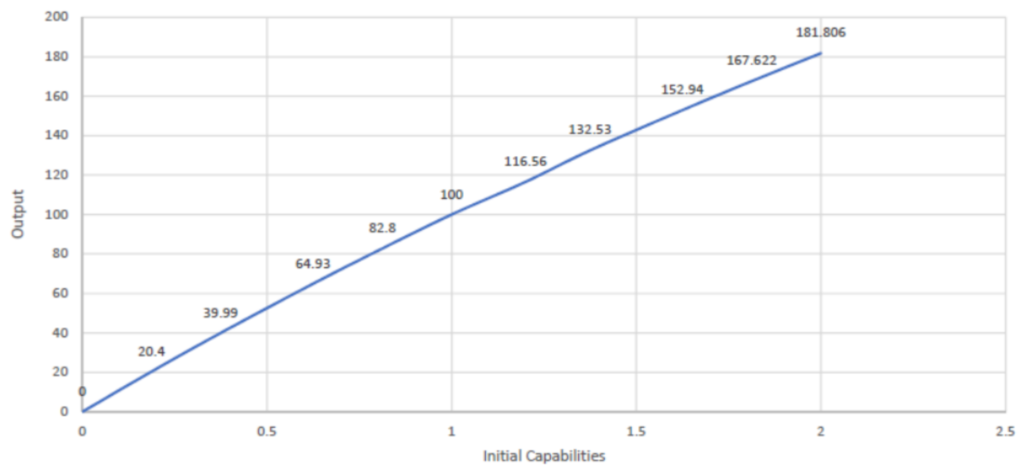


Fig 28: Initial Capabilities vs. Output at the end of the simulation

Case 3: Ramp in the required output

Ramp in required output is the slope of the line representing an increase in the demand for output. Varying this parameter changes the final target output. Increasing the value of this parameter increases the output shortfall.

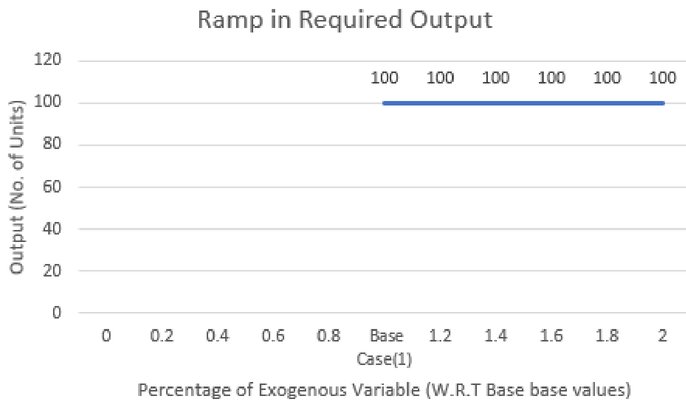


Fig 29: Increase in Ramp of required output vs. output at the end of five years

From figure 29 above we can notice that changing the value of the required output does not seem to have any effect on the output. This is not consistent with practice because realistically, companies tend to put correction measures in place when they experience an output shortfall.

This is because the values of the sensitivity of work effort to output shortfall are set as 0 in the base case. We can expect to see consistent behavior if we change the value of this parameter. We can easily verify this by setting the value of sensitivity of work effort to outcome to 1 and the value of ramp in expected output to 10 while keeping every other parameter constant (Fig 30).

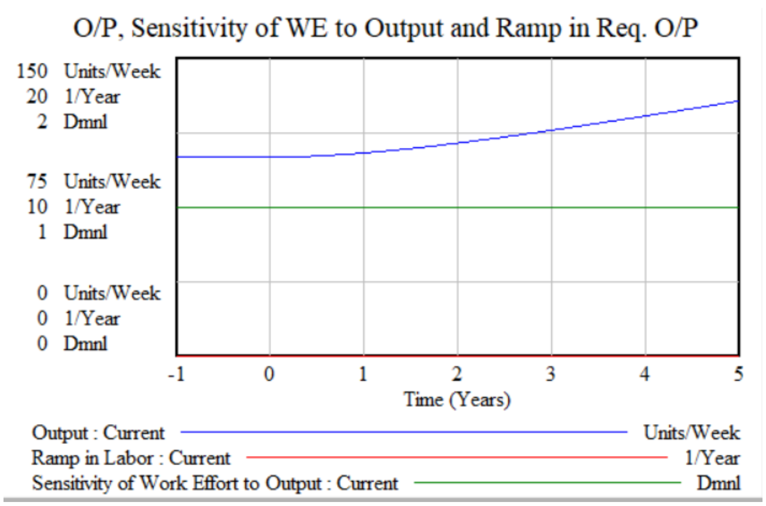


Fig 30: Behavior of Output when Ramp in required output is varied along with Sensitivity

The other sensitivity parameter associated with this can be “Sensitivity of labor to output shortfall”. However, varying this alone will not yield any result as this parameter can only affect the size of the labor force when it affects the value of required labor such that it is smaller than the value of authorized labor.

<u>Case 4: Step in required output</u>

Step in required output is the size of the step representing an increase in the demand for output. The step in required output was studied without an introduction of the slope, i.e., under different base case conditions. Increasing the value of this parameter increases the output shortfall. Unlike the previous case, this represents a one-time increase at a specified point in time. Because of this, the effect on the increase in output is different than the previous case. However, if the model is not sensitive to output shortfall it displays an identical behavior to the previous case (Fig 31).

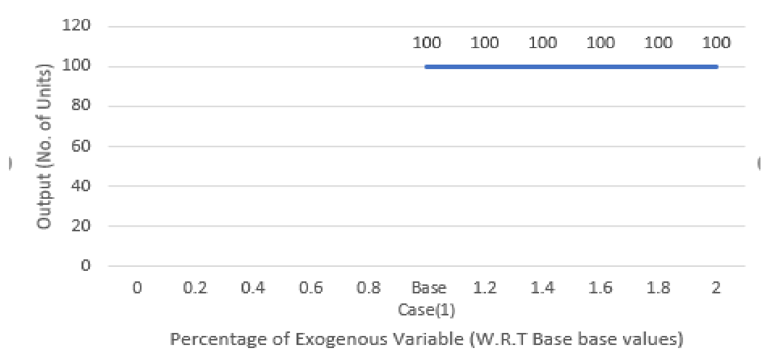


Fig 31: Increase in Step of required output vs. output at the end of five years

Similar to the previous case, we can expect to see a consistent behavior, i.e., an increase in output with increasing step size if the value of the sensitivity parameter associated with output is non-zero. This is verified by increasing the size of step to 1 and sensitivity of work effort to output to 1 (Fig 32).

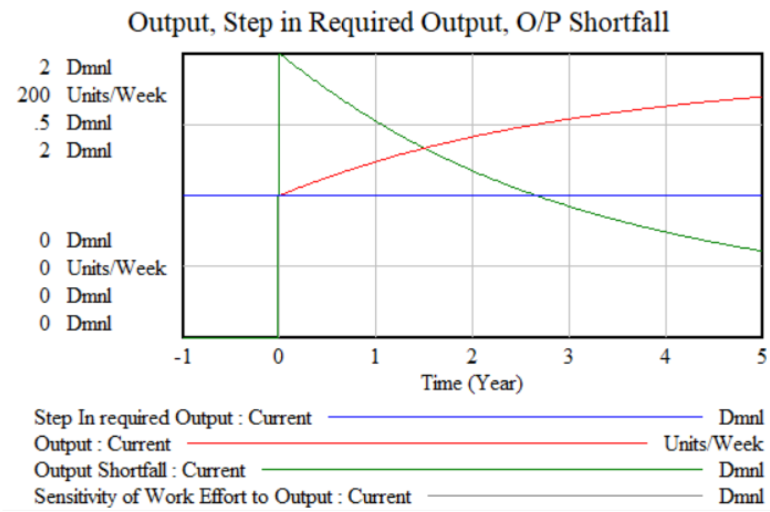


Fig 32: Behavior of Output when Step in required output is varied along with Sensitivity

Case 5: Initial required output

Initial required output represents the demand for the product at the start of the production. This value remains constant throughout the simulation. It is expected that the production is tailored to suit the demands and the output should be able to match the demand if the operation has sufficient capability.

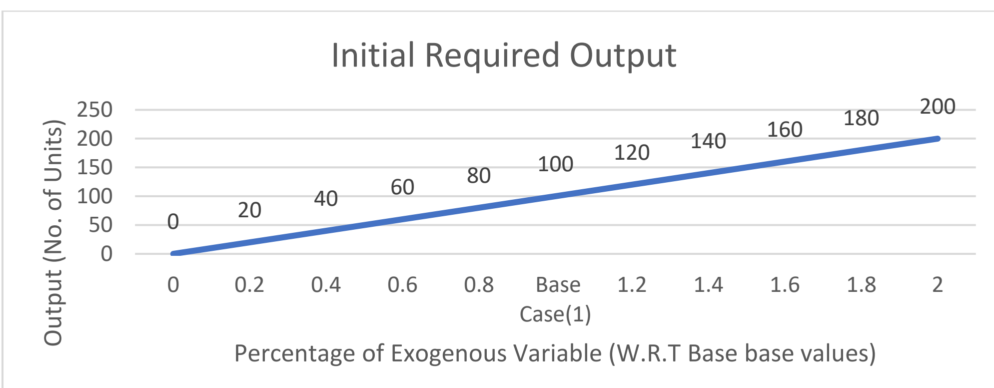


Fig 33: Increase in initial required output vs. output

Fig. 33 demonstrates a linear relationship between the required output and actual output. Initial required output affects the required output which in turn influences the output shortfall. This occurs because the model is designed to start under equilibrium conditions. However, the model does not produce additional output in response to output shortfall introduced by base case conditions.

Additionally, one can observe that the output shortfall stays at zero even when the initial required output is increased or decreased. This is because the initial required output also influences the reference productivity. As the reference productivity increases, the productivity increases and hence a greater output is achieved.

Case 6: Initial Labor

Initial labor represents the number of workers involved at the start of the operation. An increase or decrease in the number of initial laborers does not affect the output. The archetypical capability trap model is designed to start under equilibrium, this means the output will be equal to the initial required output irrespective of labor.

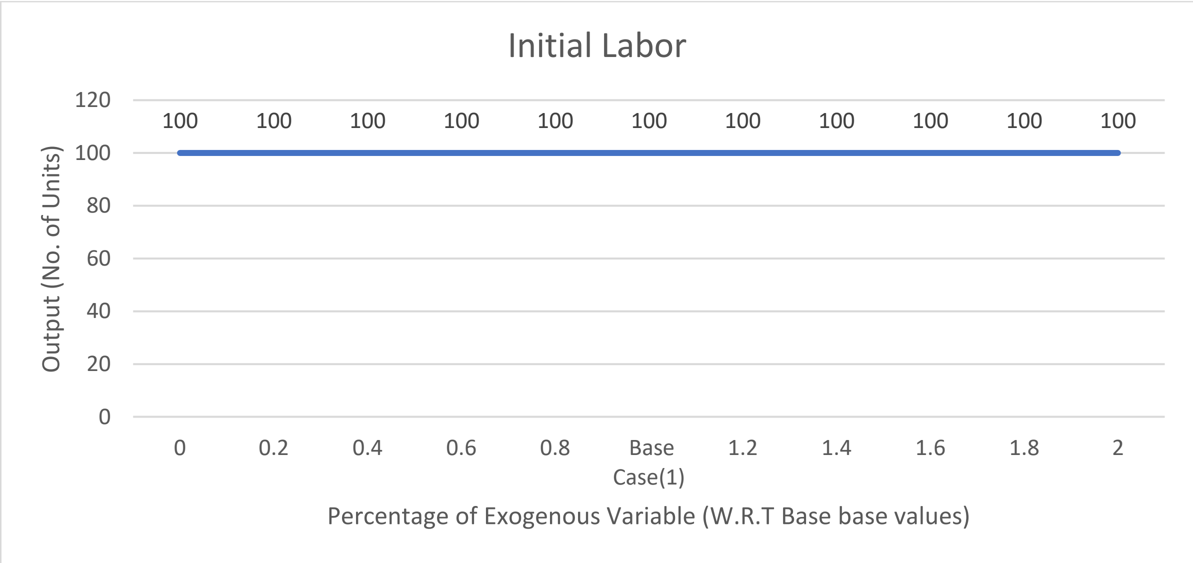


Fig 34: Increase in Initial Labor vs. output at the end of 5 years

Case 7: Sensitivity of Work Effort to Output

When firms experience output shortfall, they tend to increase their work effort. Work effort is the product of workforce size and productivity. Increasing work effort denotes increased hours toward production activities as productivity remains constant. The sensitivity of work effort to output represents the relative increase in work effort that the employees put in to cover the output shortfall.

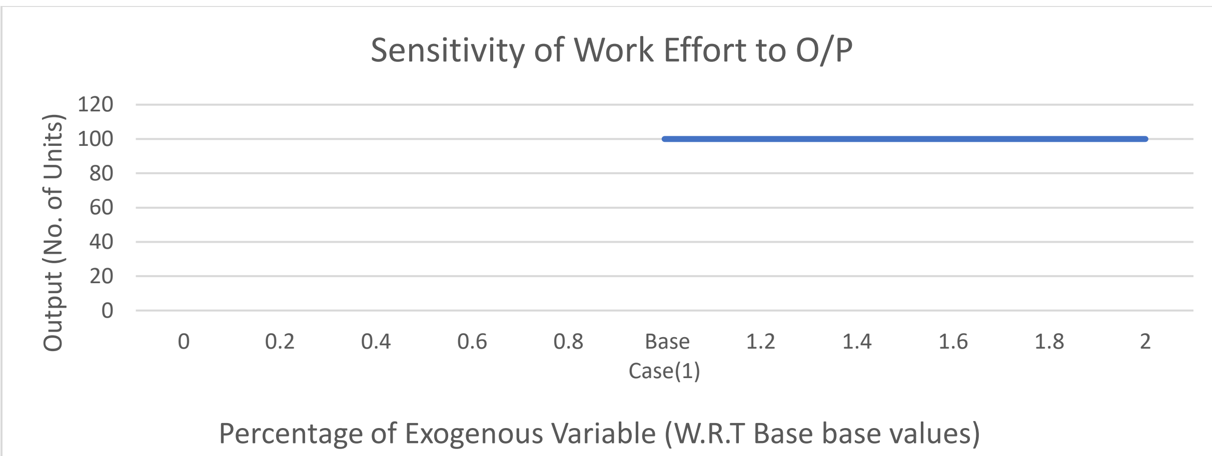


Fig 35: Increase in Sensitivity of Work Effort to Output vs. output at the end of 5 years-Base Case

Sensitivity analysis demonstrates that this parameter does not seem to affect the output. However, this is not true. Under base conditions, the output equals demand without any output shortfall. If an output shortfall were to be introduced by varying the value of ramp in the required output or step in required output, impact of this sensitivity parameter may be observed.

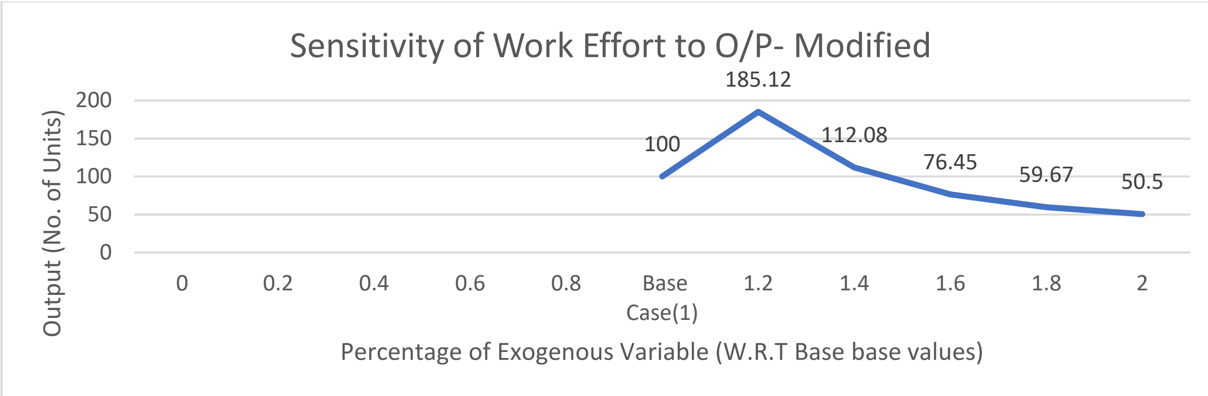


Fig 36: Increase in Sensitivity of Work Effort to Output vs. output at the end of 5 years-Modified Conditions

Fig 36 was obtained by performing sensitivity analysis while introducing a ramp in required output of 50.

As the value of sensitivity of work effort to output was increased, an increase in output followed by a decline in output at the end of five years was observed. This parameter affects the change in time spent working. As the value of this parameter is increased, the change in time spent working is also increased. While this increases the output in the short run, this occurs at the expense of time spent improving.

The resulting decline in time spent improving decreases the capability of the operation and has a detrimental effect on output.

A higher output was observed in the first two cases, i.e, 1.2-times, and 1.4-times base case values. This is because the time of simulation is relatively short to demonstrate the negative effects. This can be observed if we were to either choose a higher value of this sensitivity parameter (Fig. 30) or extend the time frame of the simulation.

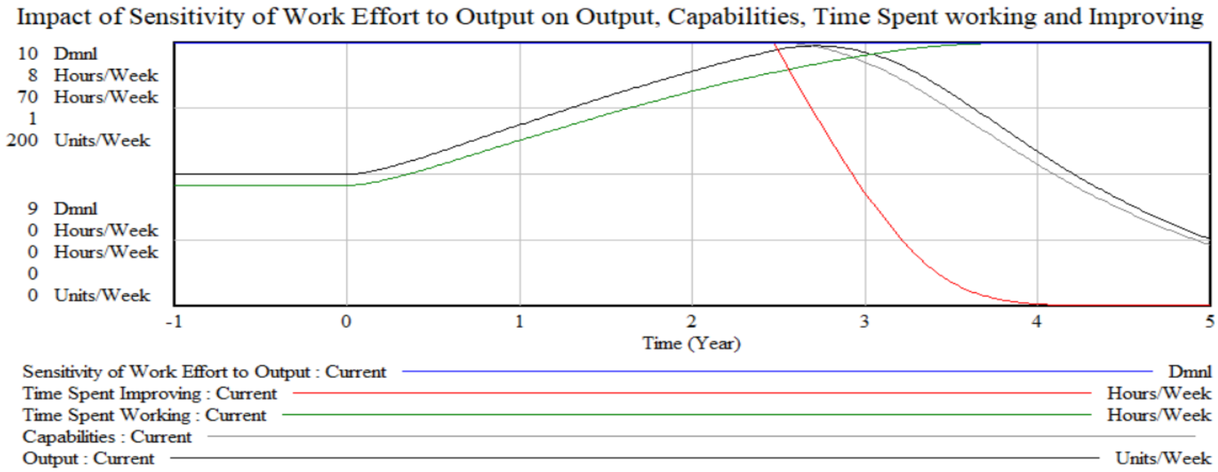


Fig 37: Impact of Sensitivity of Work Effort to Output (Value =10)

Case 8: Sensitivity of Improvement Effort to Output

When project teams experience output shortfall, they have two choices to decrease the shortfall. They can work harder or work smarter. Working smarter involves investing relatively more time in improvement programs than working, with reference to pre-output shortfall conditions.

The sensitivity of improvement effort to output represents the extent to which companies invest in developing capabilities while facing an output shortfall. This parameter affects the change in the required output.

Fig. 38 shows that there is no effect of this sensitivity parameter. This is because under base case conditions we do not have any output shortfall or increase in time spent improving.

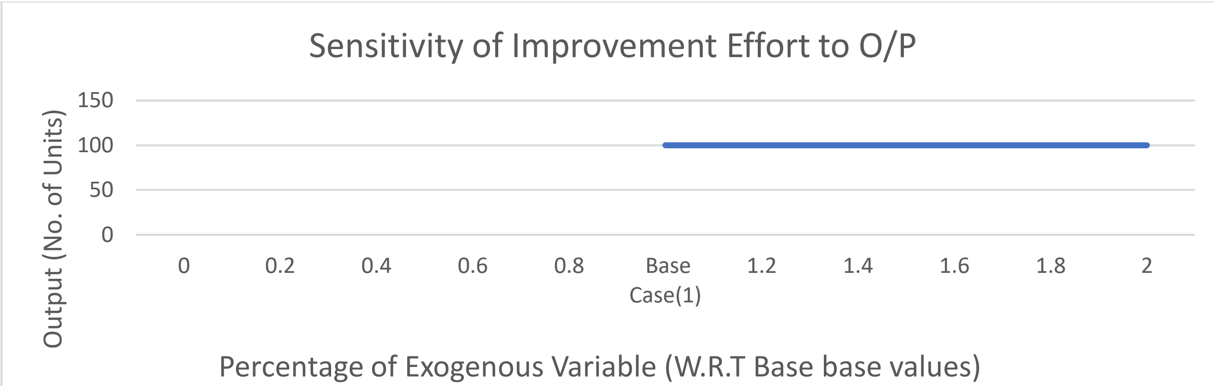


Fig 38: Increase in Sensitivity of Improvement Effort to Output vs. output at the end of 5 years- Base Case

Fig 39 was obtained by performing sensitivity analysis while introducing a ramp in required output of 50 and setting the value of the increase in time spent working to -10.

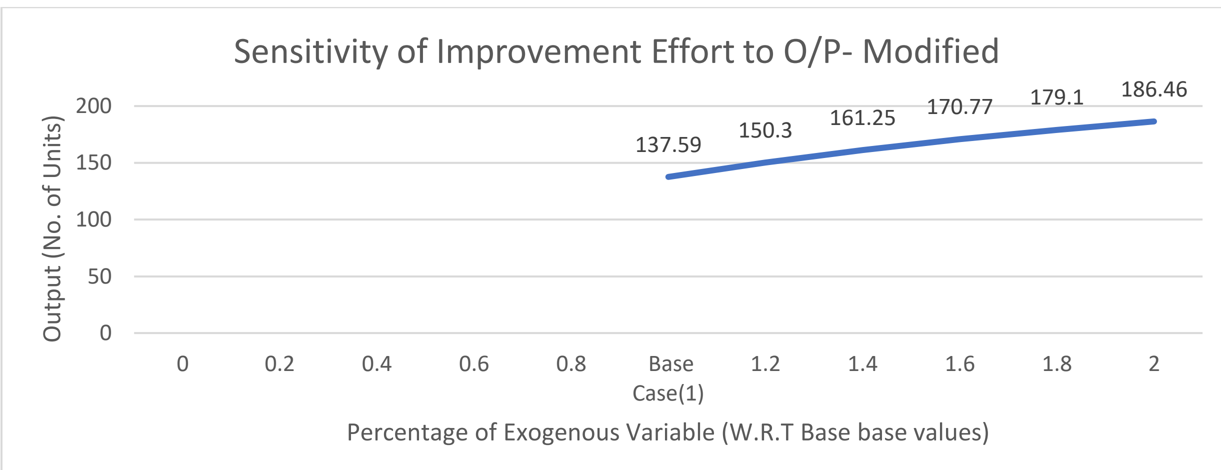


Fig 39: Increase in Sensitivity of Improvement Effort to Output vs. output at the end of 5 years- Modified Conditions

Merely increasing the time spent in improvement effort improves production and increasing the sensitivity of improvement effort to output shortfall amplifies this effect.

Case 9: Reference Fraction of Effort to Output

This represents the ratio in which the number of working hours are divided between work effort and improvement effort.

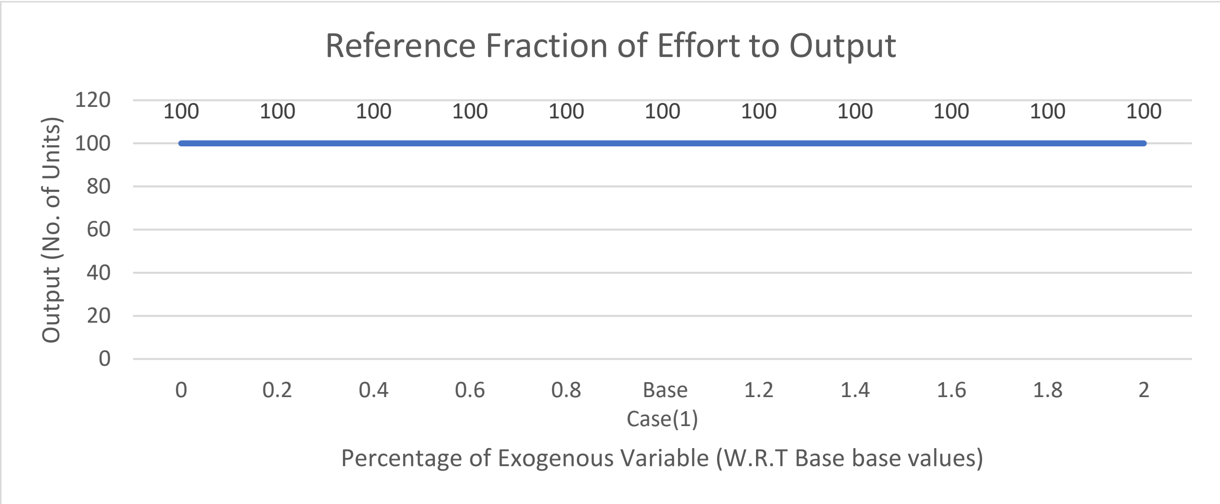


Fig 40: Increase in Reference Fraction of Effort to Output vs. output at the end of 5 years-Base Case

Reference fraction affects the time spent working, time spent improving and reference productivity. This parameter is inversely proportional to productivity and directly proportional to time spent working. The output is a product of productivity, labor and time spent working. Varying this ratio does not have any effect on the output as the product of time spent working and productivity remains constant. This is because the capability trap archetypical model is designed to start at equilibrium irrespective of starting conditions. Because reference fraction of effort to output is a starting condition, it has minimal effect on the performance of this model.

Case 10: Average Capability Loss Rate

This represents the rate at which technology or knowledge becomes obsolete thus depriving the firm of capability.

If we were to run a sensitivity analysis under base case conditions, we would observe no change in output as we vary the capability loss rate. This would mean that the rate at which technology becomes obsolete has no impact on production. This is not true, and this only happens so because, under base case conditions, inflow is the same as the outflow.

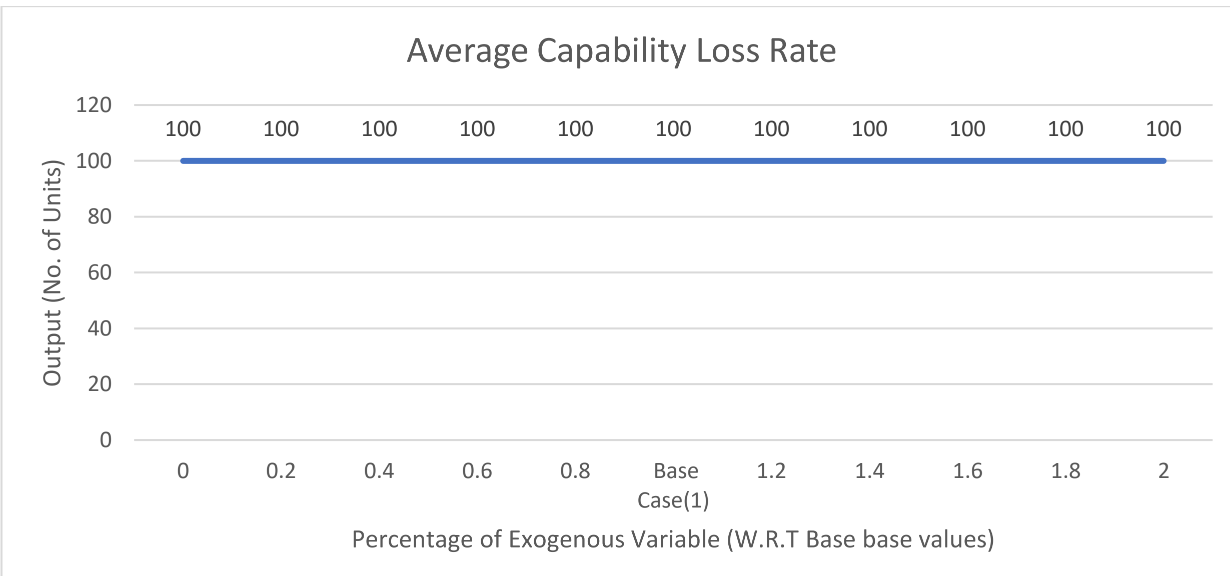


Fig 41: Increase in Average Capability Loss Rate vs. output at the end of 5 years- Base Case

The capability loss rate does not affect the capability of the system directly. However, it does affect the decrease in capability. The system attains an equilibrium over time and a decrease in capability becomes equal to an increase in capability. The rate at which this occurs depends on the average capability loss rate and the order of capability delay.

For an initial capability of 5 and a delay order of 3, a sensitivity analysis of average capability loss rate was performed, and it was found that beyond a certain rate, the value of output remained almost constant. The model failed to reach the equilibrium value for the first two test points because the length of the simulation was restricted to five years**.**

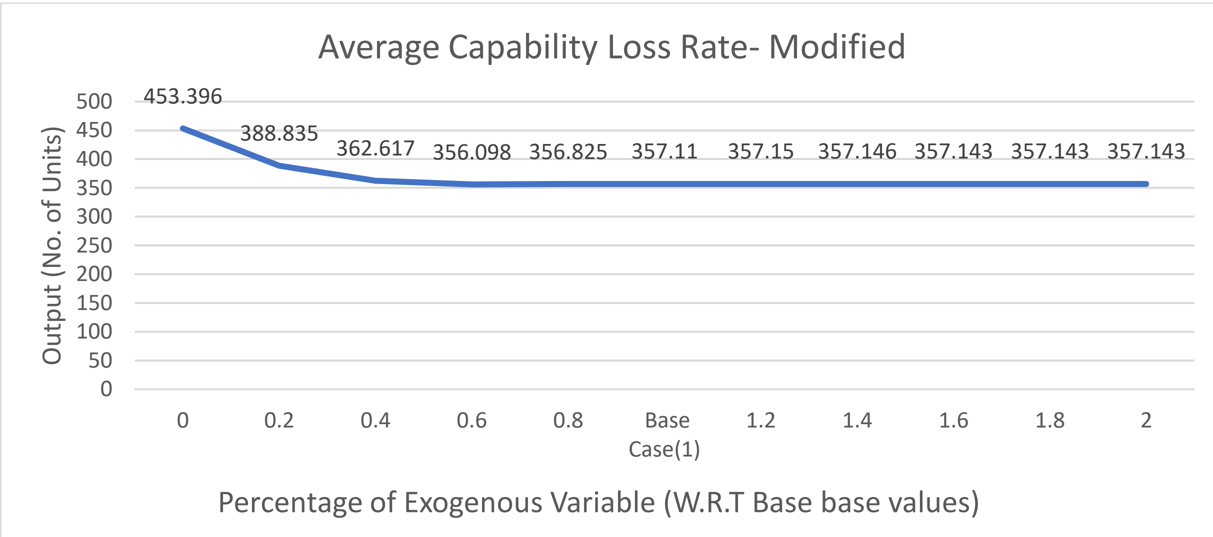
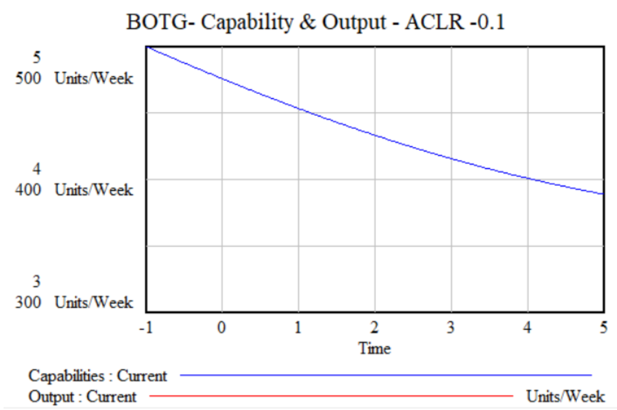
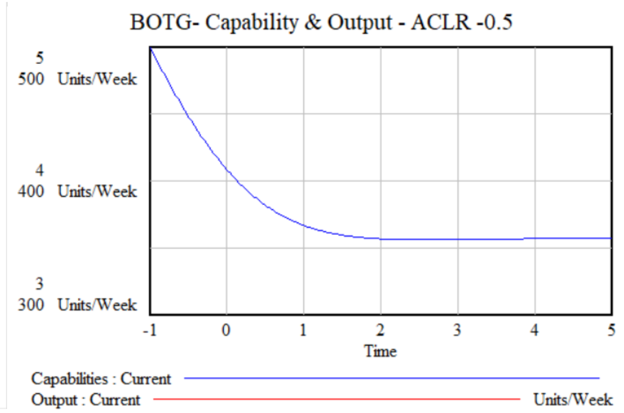


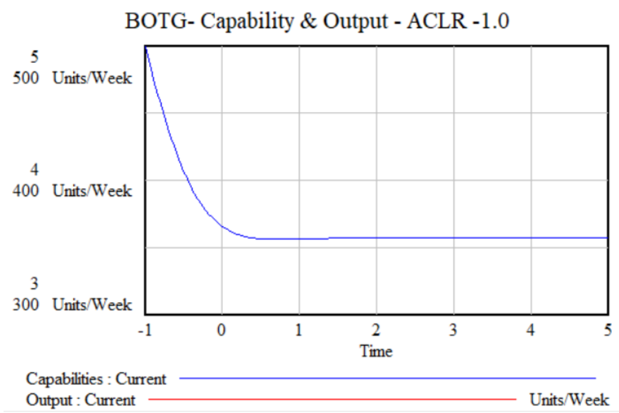
Fig 42: Increase in Average Capability Loss Rate vs. output at the end of 5 years- Modified Case

However, this does affect the value of cumulative production if measured over a period of time. This can be inferred by looking at the behavior over time graphs for capability in each of these cases.





A **B**



C

Fig 43: Behavior of Output and capability when the Average capability loss rate increases. (A) Behavior over time graphs of capability and output at an average capability loss rate of 0.1. (B) Behavior over time graphs of capability and output at an average capability loss rate of 0.5. (C) Behavior over time graphs of capability and output at an average capability loss rate of 1.0.

These figures have capabilities overlapping on output because productivity is influenced by capability and mimics the shape of capability. Also, productivity affects output.

The three figures demonstrate that while the output at the end of five years is the same, the cumulative value of output or the gross output measured is largely different. This is because the areas under the output curve get significantly smaller as the value of the average capability loss rate increases.

Project Capability Trap Model (P-C Trap Model)

Figure 44 represents the graph of univariate sensitivity analysis performed on the project capability trap model. These sensitivity graphs facilitate the estimate of the percentage change in output for a corresponding percentage change in input and provide a feel for "how sensitive" the model is to a change in the selected exogenous parameter.

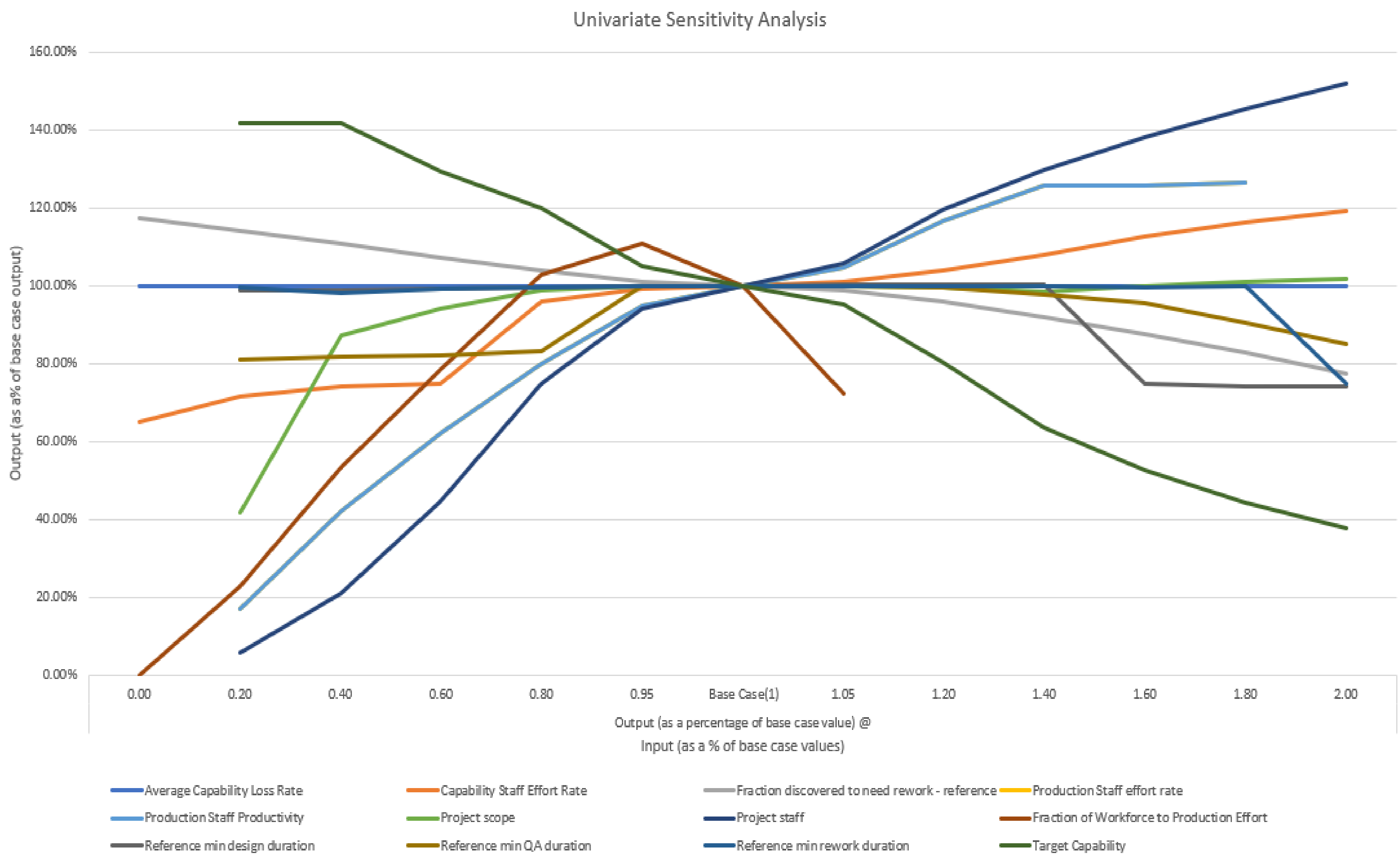


Fig 44: Univariate Sensitivity Analysis – Revised Project Model

To understand the parameters which had a high impact on the project capability trap model, a univariate sensitivity analysis was performed. Fig 44 represents the aggregate of the cases described below.

Unlike the archetypical capability trap model, no additional output shortfall was introduced. However, the entirety of the project scope serves as the equivalent of output shortfall for this model.

<u>Case 1: Average Capability Loss Rate</u>

This represents the fractional rate at which capabilities erode. The value of 0.5/year in the capability trap archetypical model was changed to 1/104 per week in the project model. Since the duration of projects tends to be shorter when compared to continuous operations, this exogenous parameter did not have any significant impact on the steady-state progress rate as seen in figure 45. This is because when this parameter is converted from year to week, its value is extremely small.

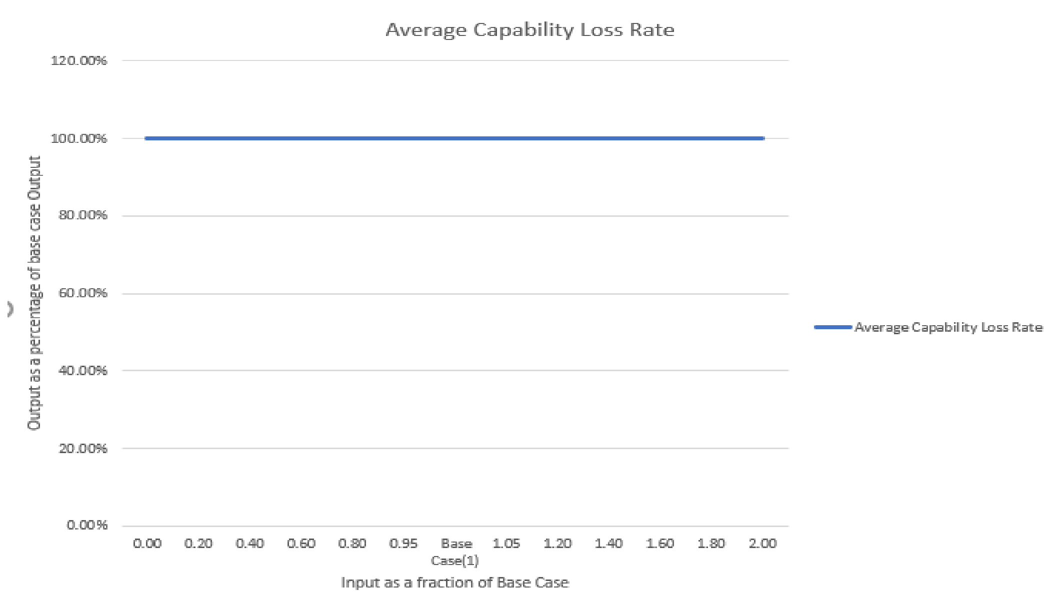


Fig 45: Graph of Average capability loss rate vs. Output

Case 2: Capability Staff Effort Rate

This parameter represents the time spent on capability development and improvement, i.e., the amount of work put in by capability staff per week. One workweek is roughly equivalent to 40 hours per week. The input value of this parameter for the base case is 1. This does seem to have a significant impact on steady-state progress (Fig 46). However, since only a small fraction of the workforce is allocated to capability development, the impact on output can be expected to be smaller in magnitude compared to the variation output in response to variation in production staff effort rate.

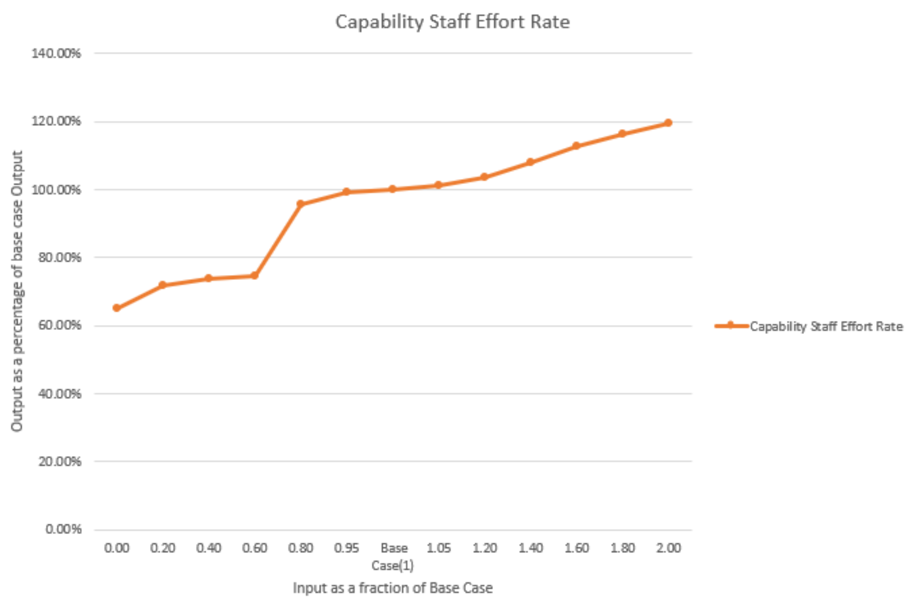


Fig 46: Graph of Capability Staff Effort Rate vs. Output

Case 3: Fraction discovered to need rework – reference

This parameter represents the fraction of work discovered to require rework that occurs regardless of the capabilities of the staff, i.e. the rework fraction if the staff has the reference (target) capabilities. The base case value for this parameter is 0.2. This is one of the few parameters which had a negative correlation with the output. As the value of this parameter decreased, the steady-state progress rate increased and vice versa (Fig 47). This negative correlation can be attributed to the fact that a smaller value of this parameter means that a larger portion of work gets approved and moves to released work.

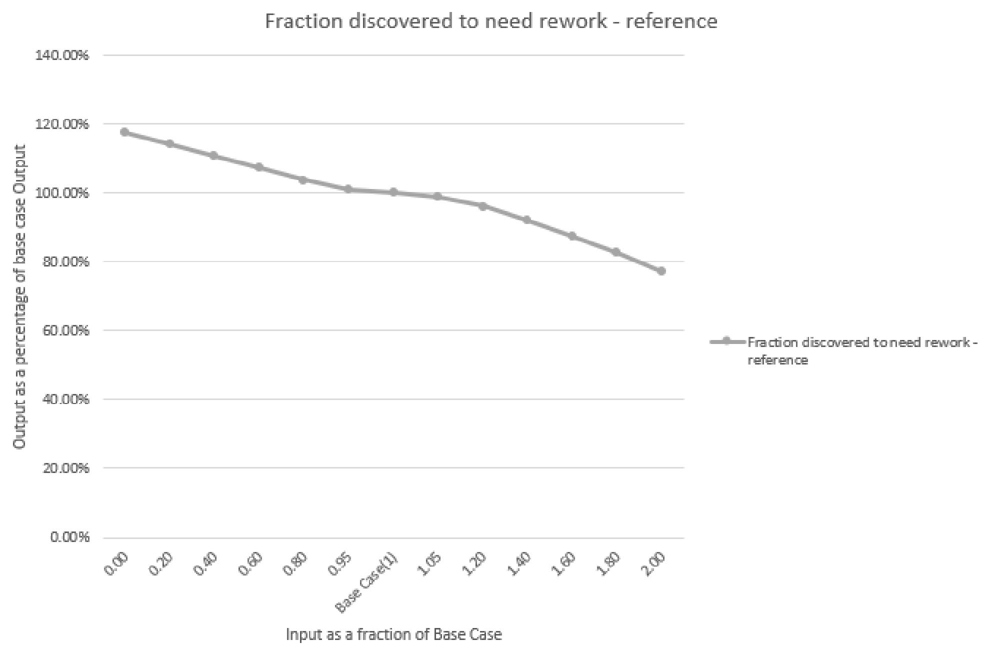


Fig 47: Graph of Reference fraction discovered to require rework vs. Output

Case 4: Production Staff Effort Rate

This parameter represents the time spent on production activities (Design, QA & Rework), i.e., the amount of work put in by production staff per week. One workweek is equivalent to 40 hours per week. The input value of this parameter for the base case is 1. This does seem to have a significant impact on steady-state progress. As a significant fraction of the workforce is allocated to production activities, the impact on output can be expected to be greater in magnitude compared to variation in capability staff effort rate as evidenced by the steeper slope of the curve (Fig 48).

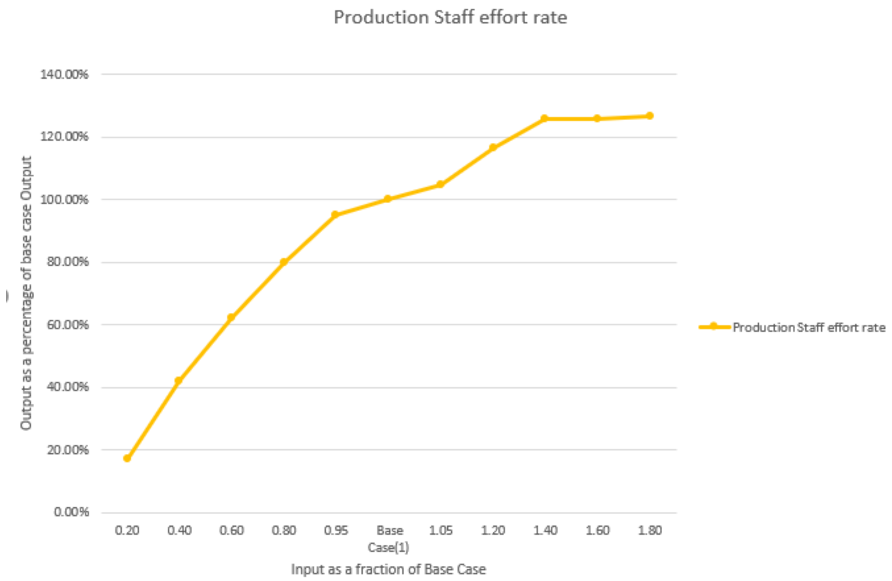


Fig 48: Graph of Production Staff Effort Rate vs. Output

Case 5: Production Staff Productivity

This parameter represents the number of work packages that a person can complete in a week. The current formulation assumes that staff productivity is constant throughout the project and across activities. The base case value is set to 1 work package per person per week. As the model is structured such that this fraction plays a similar role to the production staff effort rate, the sensitivity graphs of the model to this parameter is expected to be identical to that of production staff effort rate vs. output as evidenced in figure 49.

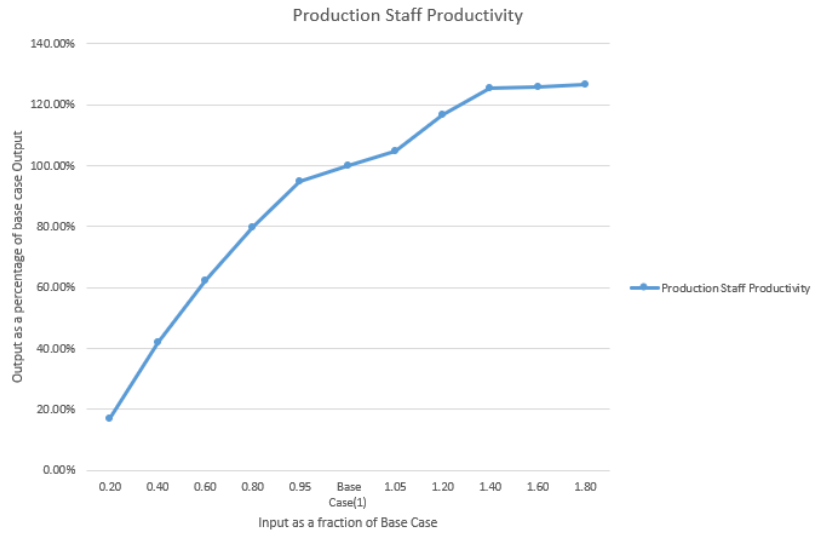


Fig 49: Graph of Production Staff Productivity vs. Output

<u>Case 6: Target Capability</u>

This represents the number of capabilities required to complete the project on time with the required quality and is assumed to be equal to the initial capabilities. This is usually an estimate set by the project manager, who identifies the resources required to complete a project efficiently. The base case value of this parameter was set to be 100 which was equal to the initial capabilities. As target capabilities varied, it was found that having target capabilities smaller than capabilities provided a much better steady-state progress rate compared to the case when the target capabilities were higher than the initial capabilities (fig 50). The higher the value of target capability, the higher the value of capability deficit fraction. A higher capability deficit fraction results in a greater error fraction and an increase in the process duration of production activities. This results in a lower steady-state progress rate.

Fig 50: Graph of Target Capabilities vs. Output

Case 7: Fraction of Workforce to Production Effort

This fraction controls the staff distribution in the project by specifying the fraction of the workforce devoted to production activities. The remainder, i.e., the absolute difference between this parameter and 1, is devoted to improvement and investment in capabilities. Upon calibration, the base case value for this parameter was found to be approximately 0.945. To ensure that future simulations were valid, an appropriate base case had to be established in which, the exogenous parameters affecting capabilities had to be calibrated such that the value of capabilities stock remained constant throughout the simulation. When the project manager shifts to work harder by distributing all resources to production, the overall steady-state progress rate slows down. If the project manager focuses entirely on work smarter by devoting excess resources to capability development, the progress rate begins to improve but then declines because there are fewer resources to keep the production activities going. If the project manager focuses on working harder only, the capabilities of the system go down causing the steady-state progress rate to decline.

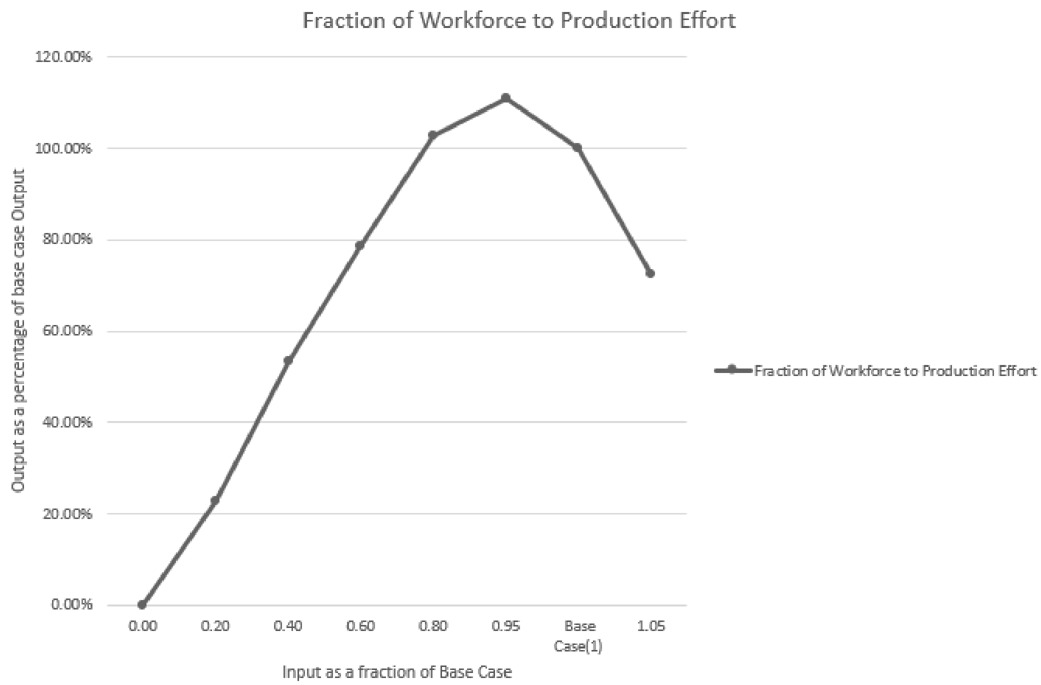


Fig 51: Graph of Fraction of Workforce to Production Effort vs. Output

<u>Case 8: Reference minimum design duration</u>

This parameter represents the minimum number of weeks a work package must stay in the design backlog until it can be constructed. However, this is only an initial value and as capability improves, the minimum design duration also decreases. This parameter does not seem to have a significant impact on output rate unless it crosses a threshold value as seen in figure 52. This is because the design is the first activity and the work progressed from the design stock may stay in the system for a considerable duration before it gets released as a final product.

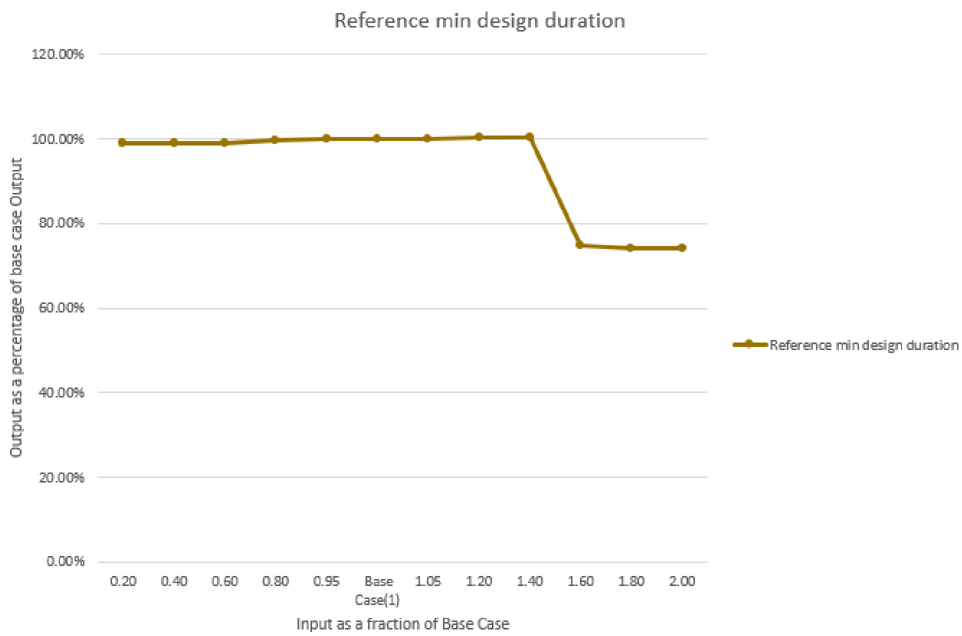


Fig 52: Graph of Reference minimum design duration vs. Output

Case 9: Reference minimum quality assurance duration

This parameter represents the minimum number of weeks a work package must stay in the quality assurance backlog until it can be checked for errors. Since quality assurance directly affects the approval rate, this parameter does seem to hold a slight influence over a steady-state progress rate. A low input value for this parameter seems to have a negative impact on the progress rate, this can be explained by excess backlog accumulating in rework backlog reducing the progress rate. The progress rate seems to be optimal when the value of this parameter is close to the value of reference values of minimum design and rework durations. This parameter influences the quality assurance process rate which in turn affects the quality assurance rate. The quality assurance rate, in turn, influences the approval rate. If the value of this parameter is small, the packages get approved faster initially and there is a duration where the quality assurance backlog is low resulting in lower approval rates thus reducing the steady-state progress. If the value of this parameter is high, the packages are approved at a slower rate resulting in a low steady-state progress rate.

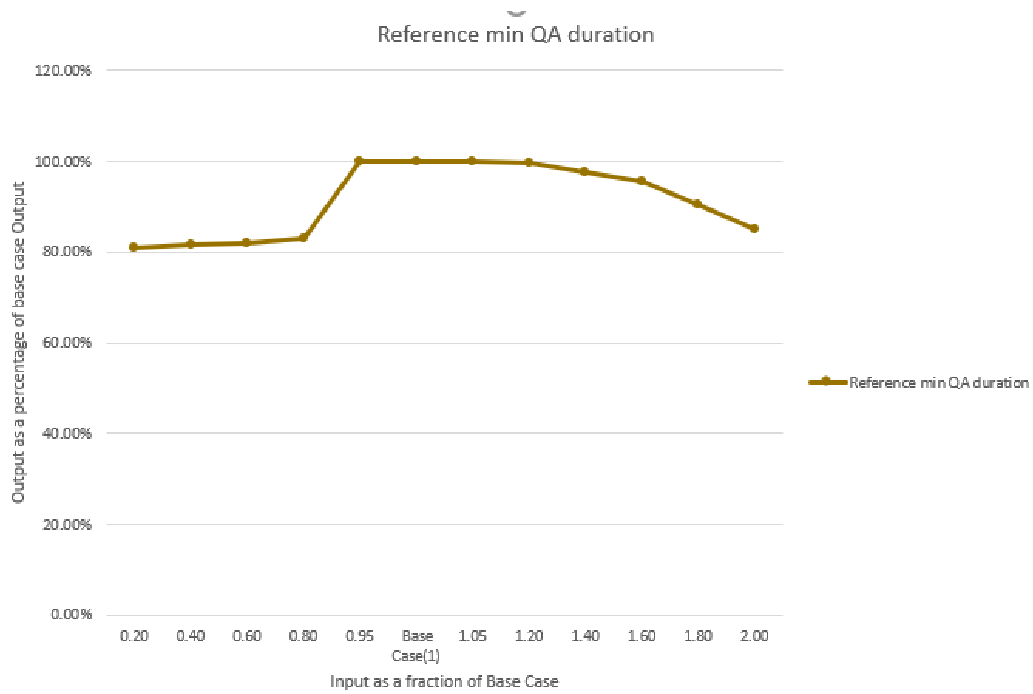


Fig 53: Graph of Reference minimum quality assurance duration vs. Output

Case 10: Reference minimum rework duration

This parameter represents the minimum number of weeks a work package must stay in the rework backlog until it can be reworked. However, this is only an initial value and as capability improves, the minimum rework duration also decreases. This parameter does not seem to have a significant impact on output rate unless it crosses a threshold value as seen in figure 54.

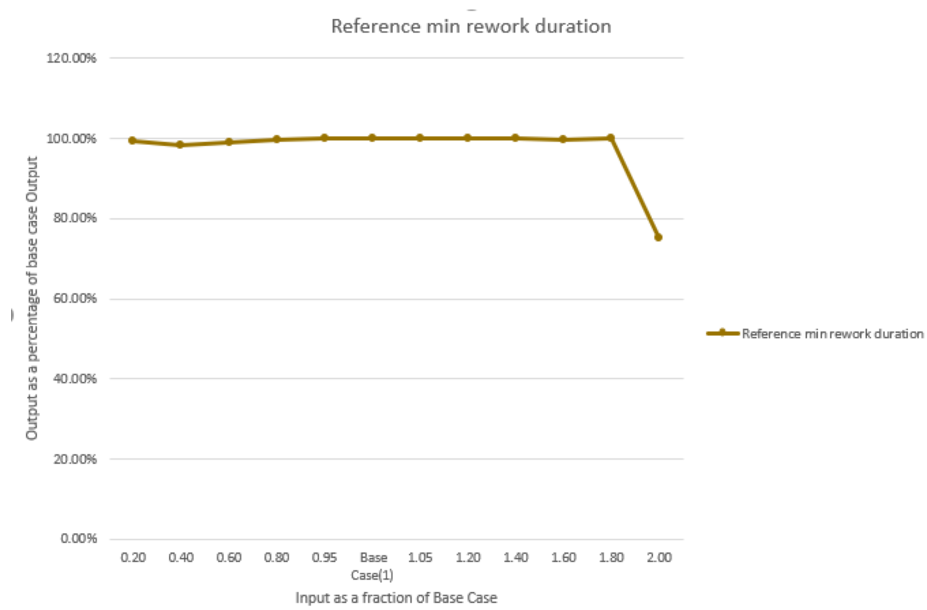


Fig 54: Graph of Reference minimum rework duration vs. Output

<u>Case 11: Project Scope</u>

This parameter represents the number of work packages that must be completed and approved to complete the project. Each work packages represents a small piece of the project. The base case value is 500 work packages. As project scope decreases, the steady-state progress rate declines too, this can be attributed to the fact that the delays, i.e. the minimum duration for design, QA & rework, become more significant.

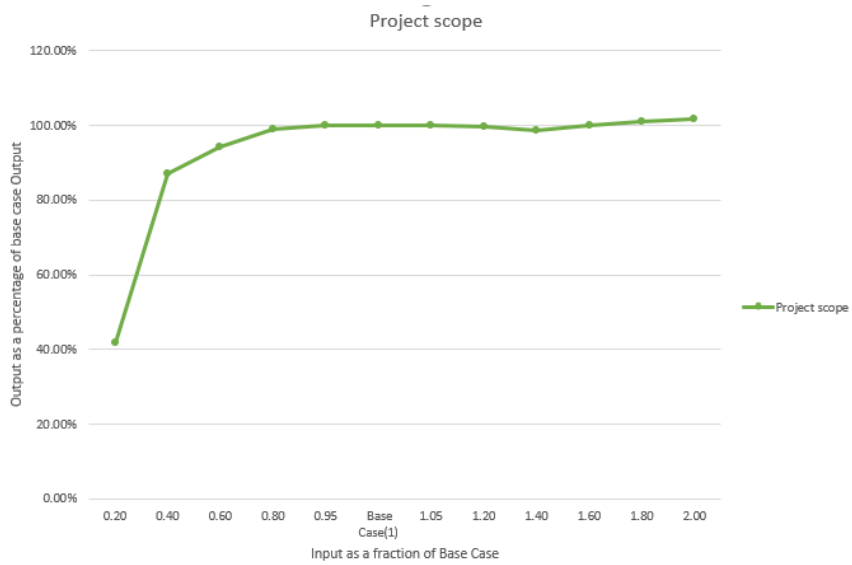


Fig 55: Graph of Project Scope vs. Output

Case 12: Project Staff

This represents the number of people assigned to the project. This parameter seems to have the most significant impact on the steady-state progress rate. The base case value for this parameter was set to 20 people. As the number of people working on the project increases, the progress rate increases linearly.

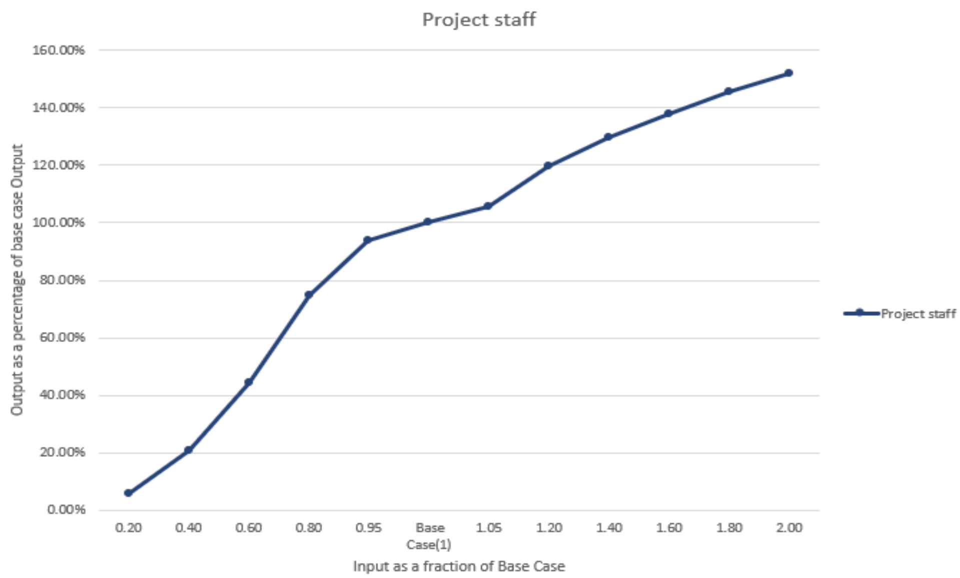


Fig 56: Graph of Project Staff vs. Output

Comparison – Archetypical Capability Trap Model Vs. Project Capability Trap Model

From the results of sensitivity analysis, it is possible to compare which parameters have a greater influence on the two models. Comparing high leverage parameters enables exploration of key differences between the two models. This will provide clarity on the second research question - how does the capability trap affect discrete projects differently than continuous operations?

Order of Influence	Archetypical Capability Trap Model	Project Capability Trap Model
1	Sensitivity of Improvement Effort to Output shortfall	Project Staff
2	Sensitivity of Work Effort to Output	Target Capabilities
3	Initial Required Output	Production Staff Effort Rate/Productivity
4	Initial Capabilities	Fraction of Workforce to Production Effort
5	Increase in Time Spent Working	Capability Staff Effort Rate
6	Ramp in Required Output	Reference Fraction Discovered to Need Rework
7	Step in Required Output	Project Scope
8	Average Capability Loss Rate	Reference Minimum QA Duration
9	Initial Labor	Reference Minimum Design Duration
10	Reference Fraction of Effort to Output	Reference Minimum Rework Duration
11		Average Capability Loss Rate

Table 1: Ranked list of high leverage parameters from both models

Parameter	Comment
Sensitivity of Improvement Effort to Output Shortfall	The larger the sensitivity, the more responsive improvement effort will be to the output shortfall. As output shortfall increases, the time spent on capability development increases.
Sensitivity of Work Effort to Output Shortfall	The larger the sensitivity, the more responsive work effort will be to the output shortfall. As output shortfall increases, the time spent on production increases.
Initial Required Output	The required output at the beginning of the simulation time.
Initial Capabilities	The initial level of capability
Increase in Time Spent Working	Represents an increase in time spent working. This occurs at the expense of time invested in capability development. A negative value of this parameter represents extra time invested in capability development at the expense of production
Ramp in Required Output	A constant increase in required output per unit period of time
Step in Required Output	A sudden one time increase in required output occurring at a specified instant of time
Average Capability Loss Rate	The rate at which capability erodes
Reference Fraction of Effort to Output	Initial Distribution of Labor Effort between output and capability development
Initial Labor	Initial Size of Workforce

Table 2: Definition of exogenous parameters- Archetypical Capability Trap Model

Parameter	Comment
Project Staff	The total size of the workforce
Target Capabilities	The number of capabilities required to complete the project
Production Staff Effort Rate	The time spent on production activities (Design, QA & Rework), i.e., The amount of work put in by production staff per week (in Workweek/week)
Production Staff Productivity	The number of work packages that a person can complete in a week
Fraction of Workforce to Production Effort	The fraction of the workforce assigned to production activities. Rest of the workforce is assigned to improvement and investment in capabilities
Capability Staff Effort Rate	The time spent on capability development and improvement. The amount of work put in by capability staff per week (in Workweek/week)
Reference Fraction Discovered to Need Rework	The fraction of work discovered to require rework that occurs regardless of the capabilities of the staff, i.e. the rework fraction if the staff has the reference (target) capabilities
Project Scope	The number of work packages that must be completed and approved to complete the project.
Reference Minimum QA Duration	The minimum number of weeks work packages must stay in the QA backlog until it can be Checked
Reference Minimum Design Duration	The minimum number of weeks work packages must stay in the design backlog until it can be constructed
Reference Minimum Rework Duration	The minimum number of weeks work packages must stay in the rework backlog until it can be reworked
Average Capability Loss Rate	The rate at which capability erodes

Table 3: Definition of exogenous parameters- Project Capability Trap Model

Does the capability trap affect projects and continuous operations in the same manner?

No, it does not. Table 1 demonstrates that the high leverage parameters for the two models are different. Sensitivity parameters play a key role in the archetypical capability trap model; however, sensitivity parameters were found to a minimal effect on the project capability trap model. The size of the workforce was found to have a very profound effect on output in the project capability trap model, but this does not seem to affect the archetypical capability trap model. This is because the archetypical capability trap model starts in a state of equilibrium where the output is equal to the initial required output irrespective of the size of the workforce, a project never starts in equilibrium and nor does it ever really stay in equilibrium, although it does get close to equilibrium during part 2 (Fig 14).

The distribution of resources between production and capability development, while significant in both models, appears to have a higher impact on continuous operations than projects. The top two high leverage points in continuous operations, assuming the size of the workforce to be constant, are “Sensitivity of Improvement Effort to Output Shortfall” and “Sensitivity of Work Effort to Output Shortfall”. These two parameters actively adjust either the work effort or improvement effort at the expense of the other, essentially shifting the system from work harder to work smarter. In the project model, the distribution of resources ranks as the fourth most influential parameter. Additionally, the reference fraction of effort to output in the archetypical capability trap model is an initial condition such that the model starts at equilibrium and this does not have an impact on the project.

In the project model, production or capability staff work effort in workweek has a greater impact on the progress rate. An equivalent factor does not appear in the list of high leverage parameters in the archetypical capability trap model. This is because the archetypical project model starts at equilibrium and the output remains constant irrespective of the length of the workweek. We can observe that capabilities have a strong impact on both models but in meaningfully different ways. Initial capabilities are the fourth most influential parameter in capability trap model and Target capabilities are the second most influential parameter in the project model. While these may sound similar, they are different as defined in tables 2 & 3. Initial capabilities do not have a significant influence on the project model. The archetypical capability trap does not define a target capability trap because the target, i.e. the required output, is variable whereas a project scope is fixed in nature.

In the capability trap model, the project team is required to produce output continuously. This parameter can be compared to the project scope in the project capability trap model; however, the project scope is finite. It can be observed that the initially required output has a greater impact on continuous operations than the project scope does on the project model. The effect of varying required output in both cases seems to be very similar - this can be seen by comparing the relative positions of ramp step in required output in the archetypical project model and Project scope in the Project Capability Trap model.

In the archetypical capability trap model, initial conditions appear to have a more significant impact on the project when compared to the project capability trap model. This indicates that the project managers, to be successful, have to plan for long term production in continuous operations. Improving the sensitivity of the process to output shortfall appears to be the key to achieve production goals.

Both models demonstrate that working smarter by investing in capability development yields better results than working harder. **However, the project model also demonstrates that excessively investing resources in capability development efforts can be detrimental to the project progress rate.**

Archetypical Capability Trap Model		Project Capability Trap Model	
Parameter	**Order of Influence**	**Parameter**	**Order of Influence**
Variables related to the scale of effort required		**Variables related to the scale of effort required**	
Initial Required Output	**3**	**Project Scope**	**7**
Ramp in Required Output	**6**	**Reference Fraction Discovered to Need Rework**	**6**
Step in Required Output	**7**	**Target Capabilities**	**2**
		Reference Minimum QA Duration	**8**
		Reference Minimum Design Duration	**9**

Table 4: Categorization of high leverage parameters

Archetypical Capability Trap Model		Project Capability Trap Model	
Parameter	**Order of Influence**	**Parameter**	**Order of Influence**
		Reference Minimum Rework Duration	**10**
Average Order of Influence	**5.33**	**Average Order of Influence**	**7**
Variables related to the scale of resources/effort Provided		**Variables related to the scale of resources/effort Provided**	
Initial Labor	**10**	**Project Staff**	**1**
Initial Capabilities	**4**	**Production Staff Effort Rate**	**3**
Average Capability Loss Rate	**3**	**Production Staff Productivity**	**3**
		Capability Staff Effort Rate	**5**
		Average Capability Loss Rate	**11**
Average Order of Influence	**5.67**	**Average Order of Influence**	**4.6**

Table 4: Continued

Archetypical Capability Trap Model		Project Capability Trap Model	
Parameter	**Order of Influence**	**Parameter**	**Order of Influence**
Variables related to the allocation of resources		**Variables related to the allocation of resources**	
Sensitivity of Improvement Effort to Output Shortfall	**1**	**Fraction of Workforce to Production Effort**	**4**
Sensitivity of Work Effort to Output Shortfall	**2**		
Increase in Time Spent Working	**5**		
Reference Fraction of Effort to Output	**9**		
Average Order of Influence	**4.25**	**Average Order of Influence**	**4**

Table 4: Continued

The high leverage parameters examined in both models can be grouped into three categories as shown in Table 4; Variables related to scale of effort required, Variables related to scale of resources/ effort and Variables related to the allocation of resources. The order of influence for each group has been averaged to determine the most influential group in both models. A low average is favorable. From Table 4 it can be observed that for continuous operations described by the archetypical capability trap model, variables related to the allocation of resources have a greater impact compared to the other two groups. This implies that to have the most significant impact on the output of continuous operations, the manager must try to allocate resources effectively towards working smarter. From Table 4, it can be observed that variables related to the allocation of resources have the lowest average but also the average of the group of variables related to the scale of resources/effort provided is driven up by one parameter. Also, the number of parameters with a high order of influence for the project capability trap model is the most in the group of variables related to the scale of resources/effort provided. Therefore, the performance of the project capability trap model is mainly driven by the variables related to the scale of resources/effort provided. This means that to have a significant impact on project performance, the construction project manager should increase the total work effort by hiring more labor, increasing work effort or productivity of work effort. These actions relate to project controls which means **effective project controls can reduce the impact of capability traps in construction projects. The most effective way of managing capability traps in construction projects is by increasing the total work effort- increasing project staff, increasing the duration of the workweek or increasing productivity of the work effort and capability development effort.**

CHAPTER VIII

CONCLUSION

Poor project performance could be attributed to the existence of capability traps in construction systems. Existing literature on capability traps focuses on continuous operations across a wide range of industries. There exists a significant knowledge gap when it comes to capability traps and its applicability to discrete project systems. A better understanding of capability traps in construction projects can help project managers make better policy decisions. This research aims to answer two primary questions- does the capability trap have a significant impact on construction projects? How does the capability trap affect construction projects differently when compared to continuous operations? To answer these questions, a new project model was constructed. This project model included a layer of capability trap integrated into it. The new project capability trap model was verified and subjected to a univariate sensitivity analysis. To compare the effect of capability trap in construction projects to capability trap in continuous operations- the archetypical capability trap model was subjected to a univariate sensitivity analysis too.

The analysis found that capability traps, as modeled here, can have a significant effect on construction projects. A comparison between the results of sensitivity analysis provided evidence that the capability trap had different drivers in projects. However, the comparison also indicated that there were a few common high leverage parameters between the two models such as the distribution of labor effort towards production and capability development, required output, etc. It was found that the total size of the workforce had the most impact on steady-state progress rate in projects whereas, the sensitivity of improvement effort to output shortfall had the most impact in continuous operation systems. It was found that, unlike continuous operations, initial conditions do not have a significant impact on projects. The major cause of these differences in the project and continuous operations models can be traced back to the fact that continuous operations are operating in a state of equilibrium, but an ongoing project is never in the state of equilibrium.

High leverage parameters from both models can be grouped into three categories; Variables related to scale of effort required, Variables related to the scale of resources/effort and Variables related to the allocation of resources. Upon comparison among these categories, for the archetypical capability trap model, it was found that variables related to the allocation of resources were found to have the most influential parameters. This implies that in order to effectively manage a capability trap in a continuous operations system, the manager would have to allocate resources from working harder to working smarter effectively. Upon comparison among these categories, for the project capability trap model, it was found that variables related to the scale of resources/effort provided was found to have the most influential parameters. This implies that, in order to effectively manage a capability trap in a discrete project system, the project manager should scale up the total work effort by increasing the resources such as labor or equipment and total effort by increasing the man-hours invested towards both capability development and production activities and productivity of workers during those man-hours.

This work begins to fill the knowledge gap by exploring capability traps in discrete projects. Furthermore, this study gives rise to two significant observations. Firstly, capability traps can have a significant impact on project performance and secondly, capability trap affects projects in a manner that is different from its effect on continuous operations. These findings can have a significant impact on capability trap and project management research. Since capability traps were found to have a significant impact, more research may be conducted to understand the nature of capability traps in construction projects better. It was found that adding resources and increasing the total work effort is effective in managing capability traps in a project setting. This finding indicates that the capability traps behave differently in discrete projects than continuous operations. To investigate this further, the new archetypical project capability model should be further developed to replicate real-world project behavior. Given additional time, the values chosen for exogenous parameters such as average capability loss rate, reference duration of production activities, reference error fraction, etc. would be refined by gathering additional data to provide a more accurate model. This model could be used to study the dynamics of the interaction of capability traps in projects with ripple effects and other such commonly observed phenomena in discrete time-bound undertakings. Additionally, the current model only examines the dynamics of the middle phase of a project into consideration which is a significant limitation. Given additional time, the effect of capability trap on start-up and close-out phases of a project could be explored further.

This work has implications for project managers as well. This work helps project managers understand capability traps in the context of projects. This work helps the project managers realize the impact of capabilities on construction projects and its relationship to productivity. The results provided by the sensitivity test on the project capability trap, allow project managers to identify high leverage parameters in a discrete time-bound project. It was found that variables related to the scale of resources/effort provided was found to have the most influence on project performance. More specifically, project staff, production staff effort rate, production staff productivity and capability staff effort rate were found to have the most impact on project performance. All these parameters had a positive correlation with the steady-state progress rate. This means that project managers can effectively manage capability traps by simply increasing the total work effort without reducing improvement effort towards capability development. This should help project managers implement better policies and obtain better project performance by investing heavily in high leverage parameters. Finally, the high leverage parameters in this model are all linked to concepts of project controls which indicates that effective project controls can help manage capability traps effectively.

Due to limitations in time and resources, this study was limited to comparing the effect of capability traps in a project setting to capability trap in a continuous operations setting. To accomplish this, several key assumptions were made. To keep the models comparable delays in the development of capability in the project capability trap model were ignored. The model does not distribute resources to capability development dynamically. The labor in both models remained constant throughout the simulation. The parametric values used for exogenous variables in this model were based on the values used in previous models and if the study could be extended beyond the current scope of work, surveys with project managers could have allowed for better calibration of parameters in the model. Given additional time, the equations for performance measure in the project capability trap model could have been improved upon. The process of measuring the steady-state progress rate is subject to human errors in the current model. Working on skills can improve capabilities, in other words, extra work effort towards production activities can develop capabilities too; however, the model does not take this into account. Since this work gave rise to only an archetypical project capability trap model, it has to be further modified to explore capability traps in construction projects deeper. This study explores how capability traps in construction projects work, future research can be carried out to develop heuristics which the project manager can use to make better policy decisions. This study can be further expanded to study high leverage parameters in terms of correlation.

There may be significant differences between projects and continuous operations that impact capability traps. It is possible that some of those differences, under certain circumstances, could even prevent capability traps from forming. For instance, if capabilities are added a rate faster than they are lost, the capability trap would not be a trap at all. Future studies could explore if the capability traps apply to certain kinds of projects and do the trap affect all kinds of projects the same way.

The work presented here is a step towards understanding capability traps in a project setting. The model developed for this study has several assumptions and is essentially an archetypical model of its own. This is the major contribution of this study. The model developed has been supported sufficiently and can be used for future work. Prior to this work, there did not exist an existing project model archetype which included the effects of capability trap. This study has important implications for researchers as well as practitioners. The study initiated a comparison between the project capability trap model representing discrete timebound undertakings and the archetypical capability trap model representing continuous operations by analysis. By building on the archetypical model, important phenomena such as the impact of labor changes throughout the project can be investigated. The effect of capability traps on more sophisticated project models, which represent the real world more accurately, can be investigated by using this archetype.

REFERENCES

1) Taylor, T., and Ford, D.N. (2006). "Tipping Point Failure and Robustness in Single Development Projects." *System Dynamics Review*, 22(1), 51-71.

2) Ford, D.N., and Sterman, J. (1998). "Dynamic Modeling of Product Development Processes." *System Dynamics Review*, 14(1), 31-68.

3) Taylor, T., and Ford, D.N. (2008). "Managing Tipping Point Dynamics in Complex Construction Projects." *ASCE Journal of Construction Engineering and Management*, 134(6), 421- 431.

4) Ford, David., Lyneis, James., and Taylor, Timothy. (2007). Project Controls to Minimize Cost and Schedule Overruns: A Model, Research Agenda, and Initial Results.

5) James M. Lyneis, Kenneth G. Cooper, and Sharon A. Els. (2001). "Strategic management of complex projects: a case study using system dynamics." *System Dynamics Review*, 17(3), 237-260.

6) Lyneis, J. M., Ford, D.N., and Taylor, TR. (2007). "A Project Control Model." *Proc., 2007 International System Dynamics Conference*, Boston, Ma. July 23-27.

7) Ford, D. N., and Sterman, J. D. (2003). "Overcoming the 90% Syndrome: Iteration Management in Concurrent Development Projects." *Concurrent Engineering*, 11(3), 177-186.

8) David N. Ford, Stuart D. Anderson, Andrew J. Damron, Rodrigo de Las Casas, Nevzat Gokmen, and Steven T. Kuennen. (2004). "Managing Constructibility Reviews to Reduce Highway Project Durations." *Journal of Construction Engineering and Management*, 130(1).

9) Lyneis, J. M., and Ford, D.N. (2007). "System dynamics applied to project management: a survey, assessment, and directions for future research." *System Dynamics Review*, 23(2/3), 157-189.

10) Bannerman, P. L. (2008). “Defining project success: a multilevel framework.” *PMI® Research Conference: Defining the Future of Project Management*, Warsaw, Poland. Newtown Square, PA: Project Management Institute.

11) Project Management Institute. (2008) *A Guide to the Project Management Body of Knowledge (PMBOK® Guide),* 4th Edition, PMI Publication, Pennsylvania.

12) Gaddis, P. O. (1959). “The project manager.” *Harvard Business Review*, 37(3), 89-97.

13) Aljohani A., Ahiaga-Dagbui D., and Moore D. (2017). “Construction Projects Cost Overrun: What Does the Literature Tell Us?” *International Journal of Innovation, Management, and Technology,* 8(2), 137-143.

14) Flyvbjerg B. (2013). “Over Budget, Over Time, Over and Over Again: Managing Major Projects.” *The Oxford Handbook of Project Management*, Oxford: Oxford University Press, 321-344.

15) Landry, E., and Sterman, J.S. (2017). “The Capability Trap: Prevalence in Human Systems.” *35th International Conference of the System Dynamics Society,* System Dynamics Society, Cambridge, MA, 2, 963-1010.

16) Lyneis, J., and Sterman, J.S. (2016). “How to Save A Leaky Ship: Capability Traps and the Failure of Win-Win Investments in Sustainability and Social Responsibility.” *Academy of Management Discoveries*, 2(1), 7-32.

17) Repenning, N.P., and Sterman, J.S. (2001). “Nobody Ever Gets Credit for Fixing Problems that Never Happened: Creating and Sustaining Process Improvement.” *California Management Review*, 43(4), 64-88.

18) Rivera A., Le N., Kapsikar K., Kashiwagi J, and Alhammadi Y. (2016). “Identifying the Global Performance of the Construction Industry.” *Journal for the Advancement of Performance*

Information and Value, 8(2), 1-7.

19) Flyvbjerg B, Holm M.K.S, and Buhl S.L. (2004). “What Causes Cost Overrun in Transport Infrastructure Projects?” *Transport Reviews*, 24(1), 3-18.

20) Personal discussion with Dr. Charles Wolf, 2020.

21) Li Y., Jiang L., Taylor T.R.B, and Ford D.N. (2017). “Impact of Labour Controls on Tipping Point Dynamics in Large Complex Projects.” *Systems Research and Behavioral Science*, 35(1), 605-618.

22) Faghihi, V., Hessami, A.R., and Ford, D.N. (2014). “Sustainable campus improvement program design using energy efficiency and conservation.” *Journal of Cleaner Production*, 107, 400-409.

23) Guevara, J., Garvin, M.J., and Ghaffarzadegan, N. (2017). “Capability Trap of the U.S. Highway System: Policy and Management Implications.” *Journal of Management in Engineering*, 33(4), 04017004.

24) Sterman, J.S. (2000). *Business Dynamics: Systems Thinking and Modeling for a Complex World*, Irwin/McGraw-Hill, New York.

25) Morrison, J. (2012). “Process improvement dynamics under constrained resources: Managing the work harder versus work smarter balance.” *System Dynamics Review*, 28(4), 329-350.

26) Locatelli G., Invernizzi D.C., and Brookes N. (2017). “Project characteristics and performance in Europe: An empirical analysis for large transport infrastructure projects.” *Transportation Research Part A: Policy and Practice*, 98, 108-122.

27) Flyvbjerg, B., Skamris Holm, M. K., and Buhl, S. L. (2003). “How common and how large are cost overruns in transport infrastructure projects?” *Transport Reviews*, 23(1), 71-88.

28) CII. (2015). *Performance Assessment 2015 Edition*. Construction Industry Institute. Web. Retrieved from http://www.construction-institute.org/performance.

29) Kaliba C., Muya M., and Mumba K. (2009). "Cost escalation and schedule delays in road construction projects in Zambia." *International Journal of Project Management*, 27(5), 522-531.

30) Allahaim F.S., and Liu L. (2015). "Causes of cost overruns on infrastructure projects in Saudi Arabia." *International Journal of Collaborative Enterprise*, 5(1/2), 32-57.

31) Haughey D. The role of the project manager <https://www.projectsmart.co.uk/the-role-of-the-project-manager.php> (accessed 15th January 2020)

32) Bernardini D., Avaragolla Puravarga Mathada A., and Terrasoux A. (2018). "A study on the effect of labor control policies and other exogenous factors on cost." Unpublished manuscript.

APPENDIX A

CAPABILITY TRAP MODEL: MODEL SUPPORT FILE

General Notes

This document provides evidence to support that the recreated model is similar to the capability trap model developed by Lyneis and Lyneis & Sterman (2016). This model has been created using formulas intended to replicate the same behavior as that of the Capability Trap archetypical model.

The recreated model has eight variables with dimensionless units as shown in the table below. However, these variables are either sensitivity parameters, step or fractional changes or delay orders. These variables are usually defined as fractions. Some variables are related to capability and capability is defined as a dimensionless quantity similar to the original archetypical model. All these parameters were defined as dimensionless quantities in the original capability trap model. The recreated model also had 26 variables without predefined minimum or maximum. This was because minimum and maximum were only defined if necessary as done in the original capability trap archetypical model.

Module	Group	Type	Variable
Default	CAPTrap-Akhil	L	Capabilities (Dmnl)
Default	CAPTrap-Akhil	C	Capability Delay Order (Dmnl [1,6])
Default	CAPTrap-Akhil	C	Fractional Change in Workforce (Dmnl [-1,1])
Default	CAPTrap-Akhil	LI,C	Initial Capabilities (Dmnl [0,10])
Default	CAPTrap-Akhil	C	Maximum Capabilities (Dmnl)
Default	CAPTrap-Akhil	C	Sensitivity of Workforce to Capabilities (Dmnl [-1,1])
Default	CAPTrap-Akhil	C	Sensitivity of Workforce to Output Shortfall (Dmnl [0,1])
Default	CAPTrap-Akhil	C	Step In required Output (Dmnl [0,2])

Table 5: Capability Trap Model - Variables with dimensionless units

Assumption: The recreated model assumes that workers leave at a constant rate and there are no layoffs.

The recreated model has the following differences from the archetypical model:

- 52 Variables as opposed to 50 Variables in the original archetypical model. The two additional variables are added to measure cumulative output.
- The variable "Workforce" with the units of People in the archetypical model has been renamed as "Workforce" with the units of Persons in the recreated model to more accurately describe this parameter.
- Average duration of employment has a range from 0 to 10 years. Average duration of workforce was not assigned a range of values in capability trap archetypical model. Assigning a lower bound of zero prevents the average duration of employment from being a negative value.
- Sensitivity of improvement effort to output has been renamed "Sensitivity of improvement effort to output shortfall" to more accurately describe this sensitivity parameter.
- Cumulative Output – an additional stock has been added to study the behavior of total output.
- Fraction of time spent working & Fraction of time spent improving have been assigned a range of 0 to 1 to represent real conditions. These parameters represent how a typical workweek is split between improvement work effort. A value greater than 1 or less than zero for these parameters is not possible because work week is defined as the sum of time spent working and time spent improving.
- Initial workforce and initial required output have lower bound of 0 to make the model realistic. A negative value for initial workforce does implies that hired workforce would be terminated immediately. This does not happen in real world. Initial required output

indirectly measures the market demand for the product. The lowest demand for any product is zero.

- Time to change workforce has a lower bound of 0 years. This lower bound limit the model to instantaneous change. As time is unidirectional in nature, a negative value is not physically impossible.

Conceptual Model Structure

This model structure was initially described by Repenning & Sterman (2002). This has been further developed by Lyneis & Sterman (2016) who assume that productivity is a function of capability and these two parameters have a direct relationship. As the productivity goes up, output goes up. The purpose of ramping up the output is to reduce the shortfall to zero. In the event of an output shortfall , i.e., the output produced is less than the required output, the system tries to cover this shortfall. There are two common mechanisms of reducing the output shortfall.

The first and the most common method employed to reduce the output shortfall is to increase the time spent working, i.e., the firm can ramp up production. This produces instantaneous results. However, this is done at an expense of time reserved for training/learning program. Over a period of time, this reduces capability. This mechanism makes up the work harder loop.

The second option is to train employees in new techniques which produce better yield. This does not produce instantaneous results. In fact, this reduces output instantaneously. However, this increases capability over period of time as the workers are well equipped with new technology. This mechanism makes up the work smarter loop.

The model also recognizes that workforce is not constant. The firm needs workforce to produce output. Workforce is hired when it is both required and authorized by the firm. The model has delays reflecting that hiring and attrition of workforce is not instantaneous.

Causal Loop Diagram

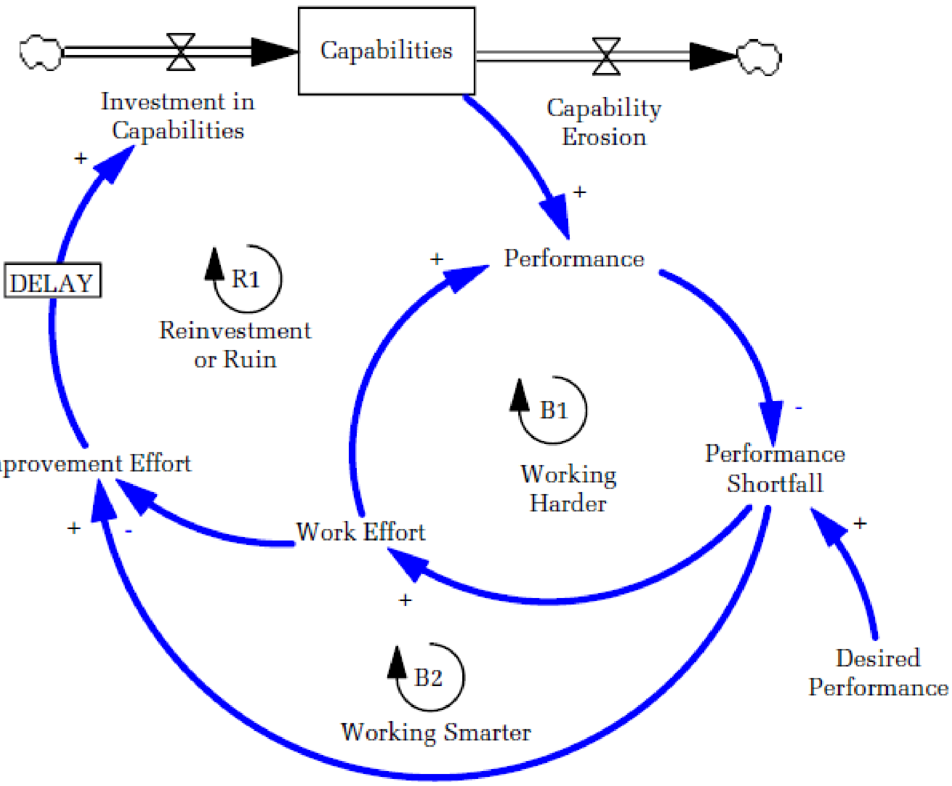


Fig 57: Capability Trap- Causal Loop Diagram, reprinted from Lyneis & Sterman (2016)

The capability trap archetypical model consists of three major loops as demonstrated in Fig 57. When there exists a shortfall in the output, firms seek to fix it by increasing output. There are two ways of accomplishing this, by making employees work harder (Loop B1) or training employees to increase their productivity (Loop B2). Since the firms have fixed working hours employing, choosing one of these methods means cutting time for the other method. Increasing work effort happens at the expense of time involved in improvement effort and vice versa. Since capability erodes over time (knowledge and techniques become obsolete) the productivity of workers keeps declining over a period of time and if the firms choose to opt for the work harder option over a long period of time, they lose productivity to such an extent that even though their workers are working longer hours than before, their output decreases. On the other hand, increasing improvement effort increases capability over time and workers deliver a greater output for the same number of work hours. Therefore, based on the overall benefits, the work smarter loop may appear more desirable. However, opting for improvement effort occurs at the expense of work effort which means significant increase in output shortfall in the short term. This could lead to managers losing their jobs (Loop R1).

Formal Model Structure

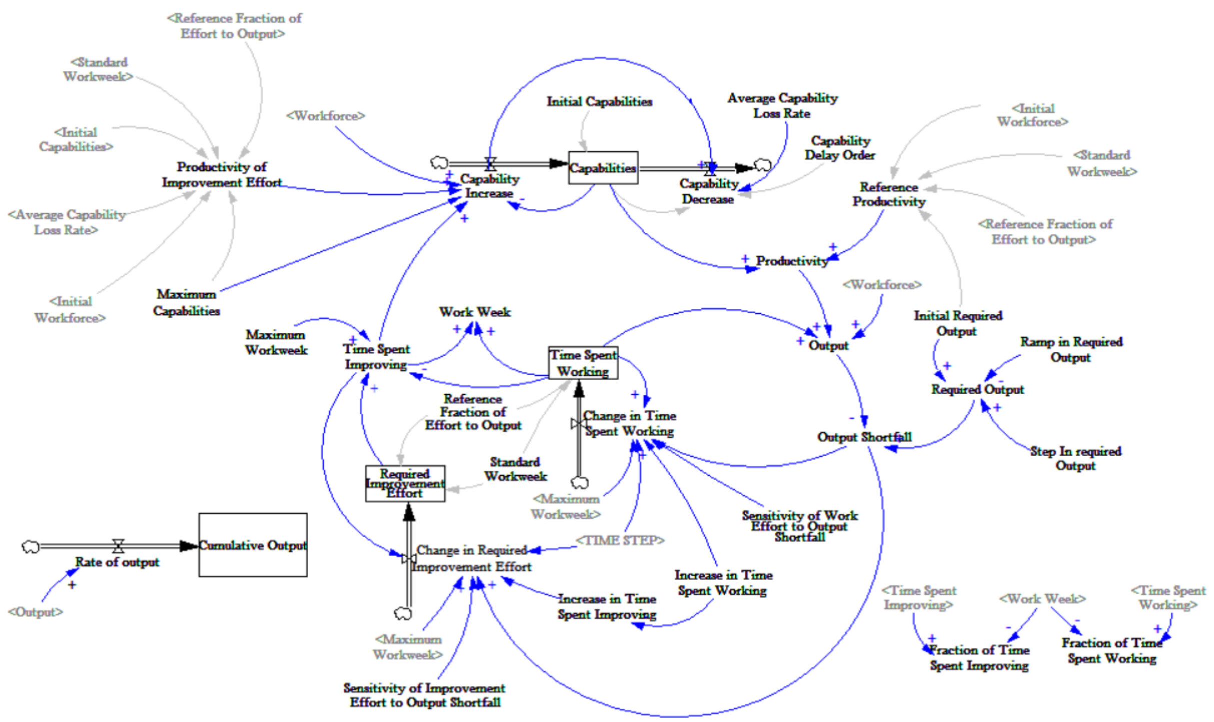


Fig 58: Capability Trap Archetypical Model (based on Lyneis & Sterman, 2016)

The formal model has additional components as shown in figures 58 and 59. This model is largely based on the model developed by Lyneis & Sterman (2016). Additional components to the capability trap archetypical model have been added to measure cumulative output. Workforce has been renamed as workforce to provide a more accurate description as shown in figure 59.

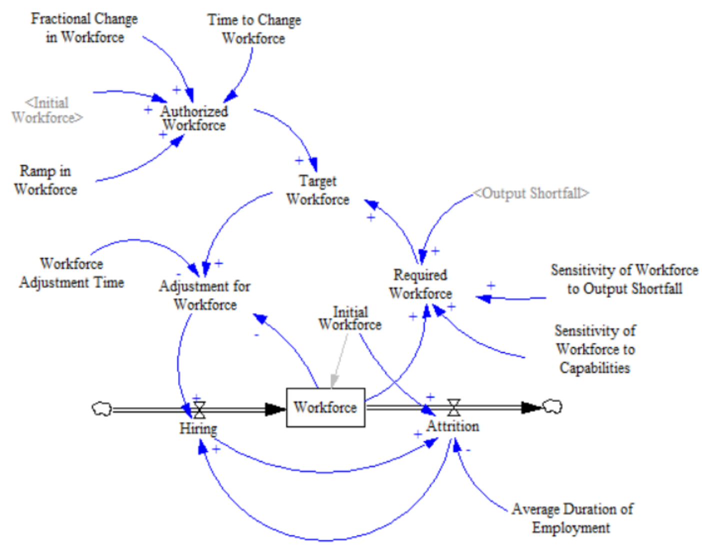


Fig 59: Capability Trap Model –Workforce (based on Lyneis & Sterman, 2016)

Documented Model Equations

The equations for the reconstructed model are based on the original capability trap archetypical model built by Lyneis & Sterman. The capability trap archetypical model can be accessed by downloading the interactive simulation at http://jsterman.scripts.mit.edu/Online_Publications.html#HowToSave

(01) Adjustment for Workforce=(Target Workforce-Workforce)/Workforce Adjustment Time

Units: People/Year

Workforce is constantly adjusted to meet the demand or Target. This Variable determines how quickly the size of workforce reaches the targeted workforce size.

(02) Attrition=DELAY3I(Hiring, Average Duration of Employment , Initial Workforce/Average Duration of Employment)

Units: People/Year

Workers stay with the firm for a period given by the average duration of employment; the attrition profile is a third order Erlang lag. This is the rate at which workers leave the firm.

(03) Authorized Workforce=Max(0,Initial Workforce*(1+STEP(Fractional Change in Workforce, Time to Change Workforce)+RAMP(Ramp in Workforce, 0 , 6)))

Units: People

Authorized Workforce can be increased or decreased by a certain amount at time zero, or follow a linear ramp with slope "Ramp in Workforce".

(04) Average Capability Loss Rate=0.5

Units: 1/Year

The fractional rate at which capabilities erode as personnel turn over and as environmental, technological, competitive and other conditions change.

(05) Average Duration of Employment=2

Units: Year [0,10]

The average Tenure of a worker. Exogenous

(06) Capabilities= INTEG (Capability Increase-Capability Decrease, Initial Capabilities)

Units: Dmnl

The capabilities of the organization are a stock, increased by improvement effort and investment in capability development, and decreased as capabilities erode.

(07) Capability Decrease=DELAY N(Capability Increase,1/Average Capability Loss Rate, Capabilities*Average Capability Loss Rate, Capability Delay Order)

Units: 1/Year

Capabilities erode over time after a certain delay, with a mean Lag given by the reciprocal of the fractional capability erosion rate. Capability erosion is modeled as an Erlang lag. The user can specify the order of the delay. NOTE: ERLANG DISTRIBUTION IS A

FORM OF GAMMA DISTRIBUTION, THE ERLANG LAG IS THE TIME THE DISTRIBUTION TAKES TO REACH THE PEAK.

(08) Capability Delay Order = 3

Units: Dmnl [1,6]

The order of the delay governing capability erosion. Exogenous.NOTE: THE ORDER OF DELAY CAN BE EXOGENOUSLY VARIED FROM 1 TO 6 IN INCREMENTS OF 1.

(09) Capability Increase=Workforce*Time Spent Improving*Productivity of Improvement Effort*(Maximum Capabilities-Capabilities)/Maximum Capabilities

Units: 1/Year

Capabilities increase as the result of effort applied to improvement effort and capability development. Improvement is determined by the product of the workforce force, the average time per person per week spent on improvement and the productivity of improvement effort. Improvement slows, however, as capabilities approach their maximum value.

(10) Change in Required Improvement Effort=Time Spent Improving*Sensitivity of Improvement Effort to Output Shortfall*Output Shortfall*(Maximum Workweek-Time Spent Improving)/Maximum Workweek+(Increase in Time Spent Improving/TIME STEP)*PULSE(0,TIME STEP)

Units: Hours/(Year*Week)

The time spent on capability development and improvement increases in proportion to the output shortfall, with a gain determined by the sensitivity of improvement to output. The increase falls as the time spent improving approaches the maximum workweek. In addition, the time for improvement can increase exogenously by a certain amount at time zero as a test input (determined by the pulse function).

(11) Change in Time Spent Working=Time Spent Working*Sensitivity of Work Effort to Output Shortfall*Output Shortfall*(Maximum Workweek-Time Spent Working)/Maximum Workweek+(Increase in Time Spent Working/TIME STEP)*PULSE(0, TIME STEP)

Units: Hours/Week/Year

The amount of time spent working on average changes in proportion to the output shortfall. Positive shortfalls lead to an increase in hours per person spent working (vs. improvement and capability development); a negative shortfall (more output than required) leads to a reduction of hours spent working. The time spent working cannot rise above the maximum workweek, so the rate of increase falls to zero as the time spent working approaches the maximum. In addition, the time spent working can increase by a fixed amount at time zero (the Increase in Time Spent Working), using the pulse function.

(12) Cumulative Output= INTEG (Max(0,Rate of output),0)

Units: Units*Year/Week [0,?]

Total number of products produced till date

(13) FINAL TIME = 5

Units: Year

The final time for the simulation.

(14) Fraction of Time Spent Improving= Time Spent Improving/Work Week

Units: Dmnl

The fraction of the workweek spent on improvement and capability development

(15) Fraction of Time Spent Working=Time Spent Working/Work Week

Units: Dmnl [0,1]

The fraction of the workweek spent on work effort (vs improvement).

(16) Fractional Change in Workforce= 0

Units: Dmnl [-1,1]

An exogenous fractional change in the authorized workforce force representing the impact of budget cuts in the workforce. NOTE: THIS PARAMETER CAN BE EXOGENOUSLY VARIED FROM -1 TO +1 IN INCREMENTS OF 0.1

(17) Hiring=Max(0,Attrition+Adjustment for Workforce)

Units: People/Year [0,?]

Since the lower bound of this function is restricted to zero, it indicates that workforces cannot be fired and the only way to lose workforces is by attrition. Hiring replaces the workforce who leave and adjusts the workforce towards the target level.

(18) Increase in Time Spent Improving=-1*Increase in Time Spent Working

Units: Hours/Week

If additional time is allocated to working harder (as an exogenous test), the time allocated to working smarter falls by the same amount. This is because Time is a limited resource.

(19) Increase in Time Spent Working= 0

Units: Hours/Week [-10,10]

The magnitude of the exogenous increase in work effort, occurring at time zero. NOTE: THE INCREASE IN TIME SPENT WORKING CAN EXOGENOUSLY VARIED FROM -10 HOURS/WEEK TO 10 HOURS/WEEK IN INCREMENTS OF 1 HOUR/WEEK.

(20) Initial Capabilities= 1

Units: Dmnl [0,10]

The initial level of capability. Capability can refer to the extent to which a task can be done. Capability for a specific task can be defined by the user depending on the nature of the task.

(21) Initial Workforce= 100

Units: People [0,500]

The size of the initial workforce at t=0

(22) Initial Required Output=100

Units: Units/Week [0,?]

The initial value for required output. 100 can be thought of as an index value (100% of the initial level of required output).

(23) INITIAL TIME = -1

Units: Year

The initial time for the simulation.

(24) Workforce= INTEG (Hiring-Attrition, Initial Workforce)

Units: People

The size of the workforce at a given point in time. Hiring increases the population of the workforce and attrition decreases the number of workforces working for the firm

(25) Workforce Adjustment Time= 0.25

Units: Years [0,?]

Average Time over which firm seeks to close the gap between target and actual workforce force

(26) Maximum Capabilities=10

Units: Dmnl

The maximum level of capabilities determined by the user.

(32) Ramp in Workforce=0

Units: 1/Year [-0.5,0.5]

The slope of a linear ramp in authorized workforce, as a fraction of the initial workforce force. Exogenous Parameter. NOTE: RAMP IN WORKFORCE CAN BE VARIED FROM -0.5/YEAR TO 0.5/YEAR HOURS/WEEK IN INCREMENTS OF 0.05/YEAR.

(33) Ramp in Required Output=0

Units: Units/Week/Year [0,50]

The slope of a linear ramp in required output, in units per year/year added to the initial required output rate. NOTE: RAMP IN REQUIRED OUTPUT CAN BE VARIED FROM 0 UNITS/WEEK/YEAR TO 50 UNITS/WEEK/YEAR IN INCREMENTS OF 1 UNIT/WEEK/YEAR.

(27) Maximum Workweek=70

Units: Hours/Week [40,100]

The maximum average workweek for the workforce.

(28) Output=Workforce*Time Spent Working*Productivity

Units: Units/Week [0,?]

Actual output is the product of the workforce force, work hours per week spent on work effort (vs. improvement), and productivity.

(29) Output Shortfall=(Required Output-Output)/Required Output

Units: Dmnl

The gap between required and actual output, as a fraction of required output.

(30) Productivity=Reference Productivity*Capabilities

Units: Units/(Hours*Person)

For simplicity, productivity (units of output per person-hour of work effort) is proportional to organizational capabilities. Reference productivity is set to initialize the model in equilibrium.

(31) Productivity of Improvement Effort=INITIAL(Initial Capabilities*Average Capability Loss Rate*(Maximum Capabilities /(Maximum Capabilities-1))/(Initial Workforce*Standard Workweek*(1-Reference Fraction of Effort to Output)))

Units: (1/(Person*Hours/Week))/Year [0,0.01]

The productivity of improvement effort is the increase in capabilities per person-hour of improvement effort. It is set so that the simulations begin in equilibrium, with the time spent on improvement given by the standard workweek less the initial time spent working, and with the increase in capabilities offsetting capability erosion.

(34) Rate of output=Output

Units: Units/Week

Number of products produced per week

(35) Reference Fraction of Effort to Output=0.8

Units: Dmnl [0,1]

The initial fraction of the workweek devoted to output. The remainder is devoted to improvement and investment in capabilities.

(36) Reference Productivity=INITIAL(Initial Required Output/(Initial Workforce*Reference Fraction of Effort to Output*Standard Workweek))

Units: Units/(Hours*Person)

The initial value of productivity. Set to initialize the model in equilibrium.

(37) Required Improvement Effort= INTEG (Change in Required Improvement Effort, Standard Workweek*(1-Reference Fraction of Effort to Output))

Units: Hours/Week

The number of hours per person per week needed to improve capabilities, based on the cumulative response to the output shortfall. Actual improvement hours per week depend on the time available after work effort is accounted for.

(38) Required Workforce=Workforce*(1+Output Shortfall*Sensitivity of Workforce to Output Shortfall+ Sensitivity of Workforce to Capabilities)

Units: People

Required workforce increases with the output shortfall. The sensitivity of workforce to the shortfall determines how many people are sought in response to a given output gap. Required workforce will also increase to provide resources to boost capabilities, according to the Sensitivity of Workforce to Capabilities.

(39) Required Output= Initial Required Output*(1+STEP(Step In required Output, 0))+RAMP(Ramp in Required Output, 0 , 6)

Units: Units/Week

The required level of output. Set by the user; begins at the reference value, and can be increased by a certain amount, or follow a linear ramp with a user-determined slope. NOTE: FINAL TIME OF RAMP IS T= 6, SIMULATION STOPS @ T=5.

(40) SAVEPER = TIME STEP

Units: Year [0,?]

The frequency with which output is stored.

(41) Sensitivity of Improvement Effort to Output Shortfall=0

Units: 1/Year [0,1]

The larger the sensitivity, the more responsive improvement effort will be to the output shortfall. The default value is zero. Exogenous. NOTE: THE VALUE OF THIS SENSITIVITY PARAMETER CAN BE VARIED FROM 0 TO 1 WITH INCREMENTS OF 0.1

(42) Sensitivity of Workforce to Capabilities=0

Units: Dmnl [-1,1]

When this function is positive, it prompts the firm to hire more workforce to combat the capability shortfall even if there is no output shortfall. The larger the value of the function, the more responsive the hiring for a given value of capability shortfall. Exogenous. The default value of 0 indicates that hiring is totally insensitive to capability shortfall.

(43) Sensitivity of Workforce to Output Shortfall=0

Units: Dmnl [0,1]

As output shortfall increases, this function increases the need for workforce. When the value of this parameter is greater than zero, it causes the firm to hire more Workforce to decrease the output shortfall. Unless it is constrained by authorized workforce WF, actual work force will increase. Exogenous Greater the value of this function, the greater the responsiveness to a given output gap

(44) Sensitivity of Work Effort to Output Shortfall=0

Units: 1/Year [0,10]

The larger the sensitivity, the more responsive work effort will be to the output shortfall. The default value is zero. NOTE: THE VALUE OF THIS SENSITIVITY PARAMETER CAN BE VARIED FROM 0 TO 10 WITH INCREMENTS OF 0.25

(45) Standard Workweek=40

Units: Hours/Week

The average number of working hours per week. (The Normal Workweek)

(46) Step In required Output=0

Units: Dmnl [0,2]

The fractional step increase in required output. Set by the user. NOTE: THIS PARAMETER CAN BE VARIED FROM 0 TO 2 WITH INCREMENTS OF 0.1

(47) Target Workforce=MIN(Authorized Workforce, Required Workforce)

Units: People

The target used to determine hiring is the required number of workers given the output shortfall or the authorized number (based on budget or other consideration), whichever is less.

(48) Time Spent Improving=Max(0, MIN(Maximum Workweek-Time Spent Working, Required Improvement Effort))

Units: Hours/Week

The time spent on capability development and improvement is given by the required improvement effort or the time available for improvement, whichever is less.

(49) Time Spent Working= INTEG (Change in Time Spent Working, Standard Workweek*Reference Fraction of Effort to Output)

Units: Hours/Week

The average number of hours each worker spends each week producing (vs. improvement effort).

(50) TIME STEP = 0.015625

Units: Year [0,?]

The time step for the simulation.

(51) Time to Change Workforce=0

Units: Year [0,2]

The time at which the change in authorized Workforce occurs

(52) Work Week=Time Spent Working + Time Spent Improving

Units: Hours/Week

The total workweek is the sum of the time spent working and time spent improving

Model Validation

Boundary Adequacy

The important concepts addressing capability traps are endogenous to this model, i.e., all components of the work harder and work smarter loops are modeled endogenously. The boundaries of this model are the same as those of archetypical model because the reconstructed model used same equations as the archetypical model.

Structure Assessment

The recreated model conforms largely to the structure of the capability trap archetypical model except for the additional structure. This additional structure was created to study the behavior of cumulative output and the formulation used for this has been tested for robustness.

While reconstructing the model, sub-models were tested, and they were found to conform to expected behavior.

Dimensional Consistency

The recreated model has been checked for consistency of units. The equations are found to be dimensionally consistent and have real world meaning. This is consistent with the archetypical model. The changes made to the model, i.e., renaming labor as workforce and adding structure to measure cumulative output, reflect the model more accurately and they are also dimensionally consistent.

Parameter Assessment

The source of parametric evaluation for the recreated model is Lyneis & Sterman's capability traps model (http://jsterman.scripts.mit.edu/Online_Publications.html#HowToSave). The parameters used in this model have real life meaning as described in the comments.

Extreme Conditions

Model Component	**Data Range**	**Data used in simulation (Base case)**	**Extreme Values**	**Behavior**
Average Duration of Employment	[0,10]	2 Years	0 & 10	People Leave as soon as they join (error – 0 year) & people will leave after a significant amount of time (10 years). On both instances, size of workforce remains constant.
Initial Workforce	[0,500]	100 People	0 & 500	Producing output is impossible (error – 0 people) & The output is produced at a constant rate equal to the initial required output.

Table 6: Capability Trap Model – Summary of Extreme Condition Test

Model Component	**Data Range**	**Data used in simulation (Base case)**	**Extreme Values**	**Behavior**
Sensitivity of Workforce to Capabilities	[-1,1]	0	-1 & 1	Workforces start leaving as soon as they observe a drop in capability- decrease in output & Workforces start joining if a drop in capability is observed and the required workforces is less than the number of authorized workers.
Sensitivity of Workforce to Output Shortfall	[0,1]	0	0 & 1	The number of workforces required is independent of output shortfall & the number of workforces required is perfectly correlated to the output shortfall.
Time to Change Workforce	[0,2]	0 Years	0 & 2	Workforces are authorized instantaneously & it takes a couple of years to authorize any new employees.
Fractional Change in Workforce	[-1,1]	0	-1 & 1	The output & capability reduces to zero & No impact on output.
Ramp in Workforce	[-0.5,0.5]	0	-0.5 & 0.5	The output & capability reduces to zero & No impact on output.
Workforce Adjustment Time	[0,2]	0.25 years	2	No Impact on output & No impact on output
Maximum Capabilities	[0,30]	10	0 & 30	Does not affect output.
Initial Capabilities	[0,10]	1	0 & 10	No Output & very high initial output exponentially decreasing until a new equilibrium is reached.
Average Capability Loss Rate	[0,10]	0.5	0 & 10	Does not affect output or capabilities.
Capability Delay Order	[1,6]	3	1 & 6	Does not affect output or capabilities.

Table 6: Continued

Model Component	Data Range	Data used in simulation (Base case)	Extreme Values	Behavior
Initial Required Output	[0,500]	100	0 & 500	No output & high output equal to initial output requirement. Output shortfall remains unaffected.
Ramp in Required Output	[0,50]	0	0 & 50	No effect on output shortfall & increasing output shortfall.
Step in Required Output	[0,2]	0.5	0 & 2	No effect on required output & causes a step increase in required output by double the initial required output resulting in huge output shortfall.
Reference Fraction of Effort to Output	[0,1]	0.8	0 & 1	No effect on output.
Sensitivity of Work Effort to Output Shortfall	[0,10]	0.25	0 & 10	No effect on output & Increases output and length of workweek.
Increase in Time Spent Working	[-10,10]	0 Hours/ Week	-10 & 10	Causes worse before better behavior (sudden decrease in output followed by an increase in output) & causes better before worse behavior in output.
Sensitivity of Improvement Effort to Output Shortfall	[0,1]	0	0 & 1	Does not have any affect on output & Increases both output and capability
Maximum Workweek	[40,100]	70 Hours/Wee k	40 & 100	No effect on output.

Table 6: Continued

The recreated model responds better to policies than individual components. The model did not respond plausibly to extreme policies when only one parameter was varied such as reducing initial workforce to zero should have resulted in zero output, Increasing the time spent working should have increased output, increasing capability loss rate should have decreased output. These instances occurred because some of these components are used at multiple instances and could result in floating point errors if it were used for division. In other instances, the expected behavior was obtained as long as related parameters were varied accordingly.

Behavior Reproduction

On recreating Lyneis & Sterman's Capability Trap model, it was of paramount importance to verify if the equations used to build it were accurate. A simple way of achieving this would be to introduce additional work (spike in required output) into the model and vary the time between Time spent working and time spent improving. All the other exogenous parameters were maintained at their base case values.

This was accomplished this by assigning a value of 0.5 to step in required output and increasing the time spent on working by 5 hours (Fig 60). This was followed by increasing the time spent on improvement by 5 hours and assigning value of 0.5 to step in required output (Fig 61). To demonstrate that the constructed model replicated the same behavior as the capability trap archetypical model, both models were simulated under same conditions.

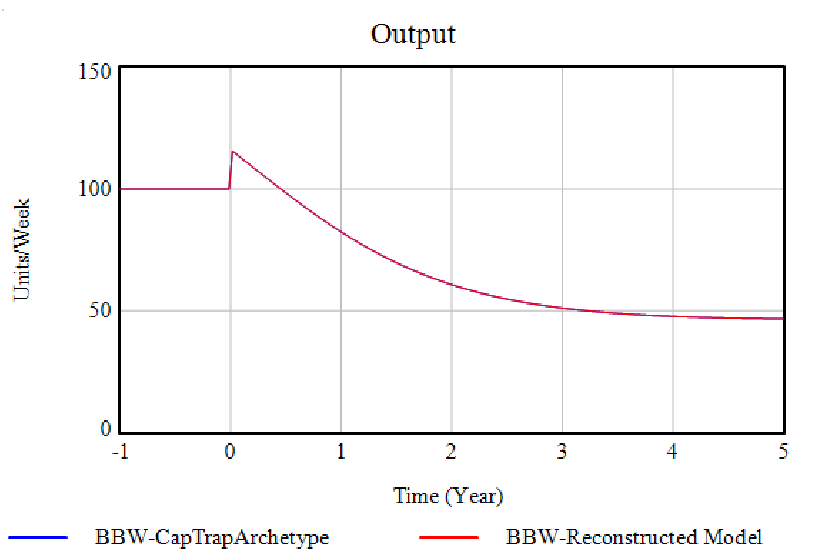


Fig 60: Better before worse behavior

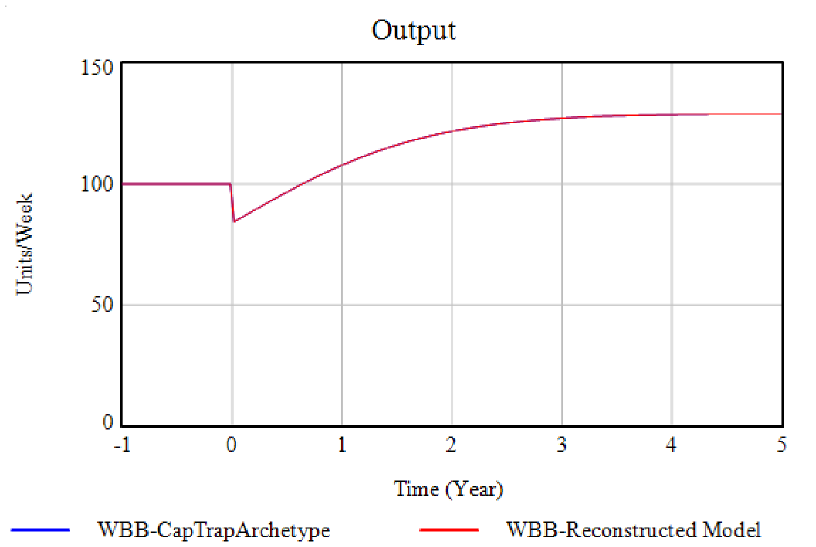


Fig 61: Worse before better behavior

From the graphs we can notice that the reconstructed model behaves perfectly as the capability trap archetypical model. The model accurately reproduces the behavior of interest which are observed in the real system.

Behavior Anomaly

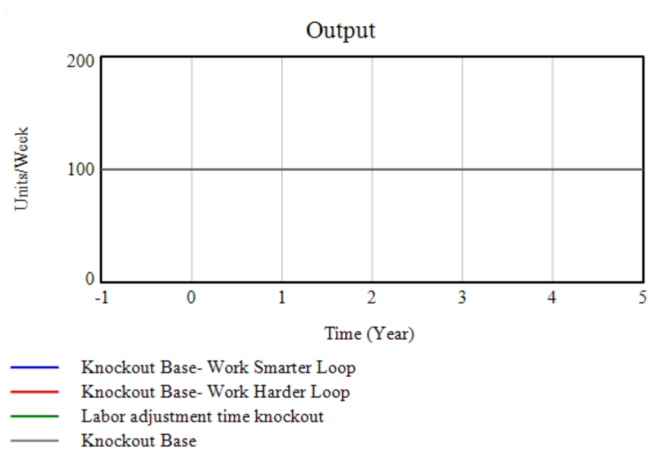


Fig 62: Loop Knockout Test, Capability Trap Model

A loop knockout test was administered on the recreated model. Due to various parameters built into this model, it proved to be robust and have a consistent behavior even when certain loops were made ineffective. While varying the reference fraction of effort to output did have an effect on time spent improving, it alone was not enough to affect capability. The results of this test were consistent with the test performed on the archetypical model.

Integration Error

The results are not very sensitive to time step or numerical integration techniques. The simulation was run for base case parameters with increase in work time spent working to 5. The graph shows the behavior of output over time for time steps equal to 0.5 years, 0.125 years, and 0.015625 years. The difference between these cases are not significant, all of them show the same behavior and attain the same equilibrium.

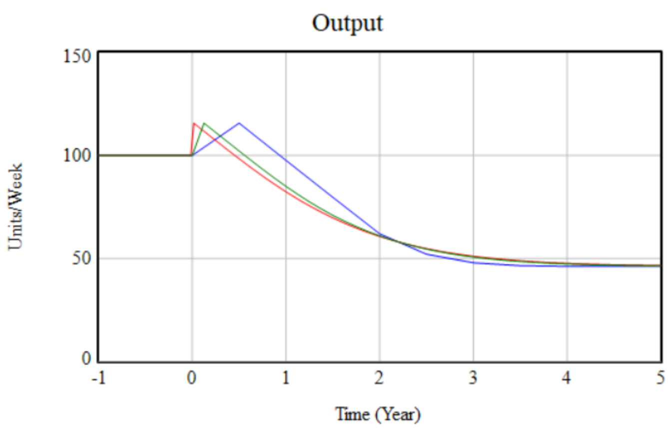


Fig 63: Sensitivity - variation in timestep, Capability Trap Model

Family Member

The reconstructed model is capable of generating different behaviors of output when parameters in the model are calibrated as demonstrated during behavior reproduction tests. In fact, this archetype has been used by researchers to demonstrate instances of system breaking down across various systems. The archetypal model has been used to demonstrate the problem with maintenance of buildings at famous universities and suggest policies to solve this problem (Lyneis & Sterman (2016); Faghihi et. al. (2014)) and to study the problem with existing highway system policies(Guevara et. al. (2017) among other things.

Surprise Behavior

The model was simulated under various time steps and for different durations. These tests also included varying all the sensitivity parameters and parameters controlling output shortfall and workforce. However, the model behaved consistently. For instance, increasing sensitivity of work effort to output shortfall increased the output but this failed when the increased work effort started eating into the hours required for improvement programs resulting in reduced capability.

Sensitivity Analysis

Univariate sensitivity analysis performed on the reconstructed model replicated the results of the analysis performed on the capability trap archetypical model. The results of this test has been included in the analysis.

Conclusion

Based on the validation tests performed on the recreated model, it can be concluded that the recreated model behaves exactly similar to the original capability trap archetypical model created by Lyneis and Sterman.

Model Use

The reconstructed model designed to replicate capability trap archetypical model by Lyneis & Sterman. By understanding this model, it is possible to design effective policies to reduce output shortfall without losing capability. The model was subjected to sensitivity analysis. This model shall be further used to replicate the capability traps occurring in construction projects by combining it with elements from the archetypical project model.

APPENDIX B

PROJECT MODEL: MODEL SUPPORT FILE

General Notes

This document provides evidence to support that the recreated project model is similar to the project model developed by Taylor and Ford (2006). This model has been created using formulas intended to replicate the same behavior as that of the archetypical project model.

The recreated model has five variables with dimensionless units as shown in table 1. However, these variables are fractions. The model has a supplementary variable to measure the duration of the project. Project Duration is solely a performance measure and is listed as a supplementary variable. The recreated model also had 36 variables without predefined minimum or maximum. This was because minimum and maximum were only defined if necessary, as done in the archetypical project model.

Module	Group	Type	Variable
Default	Akhil PM Model	A	Fraction of project backlog in design (Dmnl)
Default	Akhil PM Model	A	Fraction of project backlog in quality assurance (Dmnl)
Default	Akhil PM Model	A	Fraction of project backlog in rework (Dmnl)
Default	Akhil PM Model	C	Fraction of work packages discovered to require rework (Dmnl)
Default	Akhil PM Model	C	Scope fraction required to be considered completed (Dmnl)

Table 7: Project Model - Variables with dimensionless units

Assumptions: The recreated model assumes that the error discovery fraction, project scope, staff productivity and the number of workers allotted to the project remain constant.

The recreated model has the following differences from difference from the archetypical project model (Taylor & Ford, 2006):

- The Initial Completion Backlog has been renamed as Design Backlog and WIP. This stock will have not have any inflows. Therefore, the equation for this stock will only consist an outflow.

- Schedule pressure, project deadline and other time related constraints are not considered.
- Discovered rework will not add to further work/scope to be completed by design engineers.
- Rework fraction/ fraction of work discovered to require rework is a constant and is not affected by schedule pressure.

Conceptual Model Structure

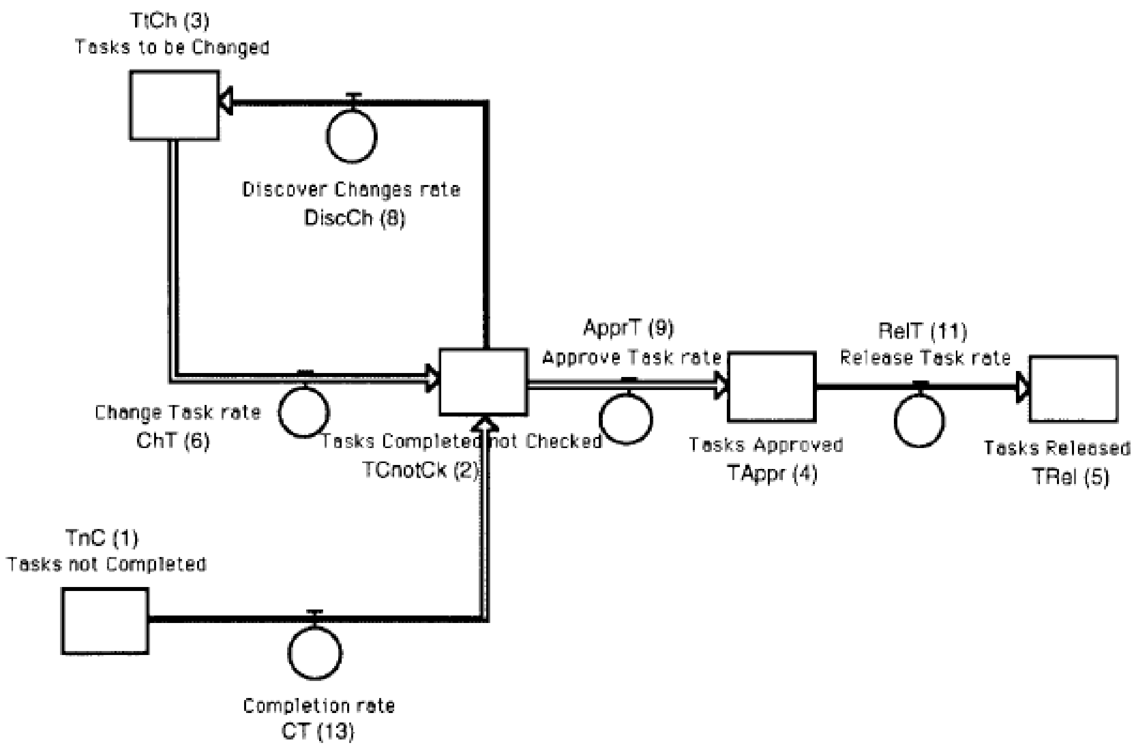


Fig 64: Project Management model – based on Ford & Sterman (1998)

This model structure was initially described by Ford & Sterman (1998). This model structure describes the workflows in a project. The model assumes that the total project scope can be broken down into fungible work packages. Initially entirety of project scope is to be designed and is used to initialize the design backlog. As the packages are designed (represented by a flow) it has to be pass certain quality standards. Upon inspection, if a work package is found to be defective, the QA engineers send it to be reworked else the package is released as completed work.

Taylor and Ford (2006) further developed the project archetypical model. This new model adds on a resource allocation sector, schedule sector and factors in ripple effect. However, for our purposes – determining the effect of capability traps in discrete projects, we will not be taking the ripple effect and schedule sector into account.

Formal Model Structure

The formal model has additional components as shown in figures 65 and 66. This model is largely based on the model developed by Taylor & Ford (2006). Components accounting for scheduling and ripple effect have been deleted from the Taylor & Ford (2006) model as it is not necessary to study the effects of capability traps in construction projects.

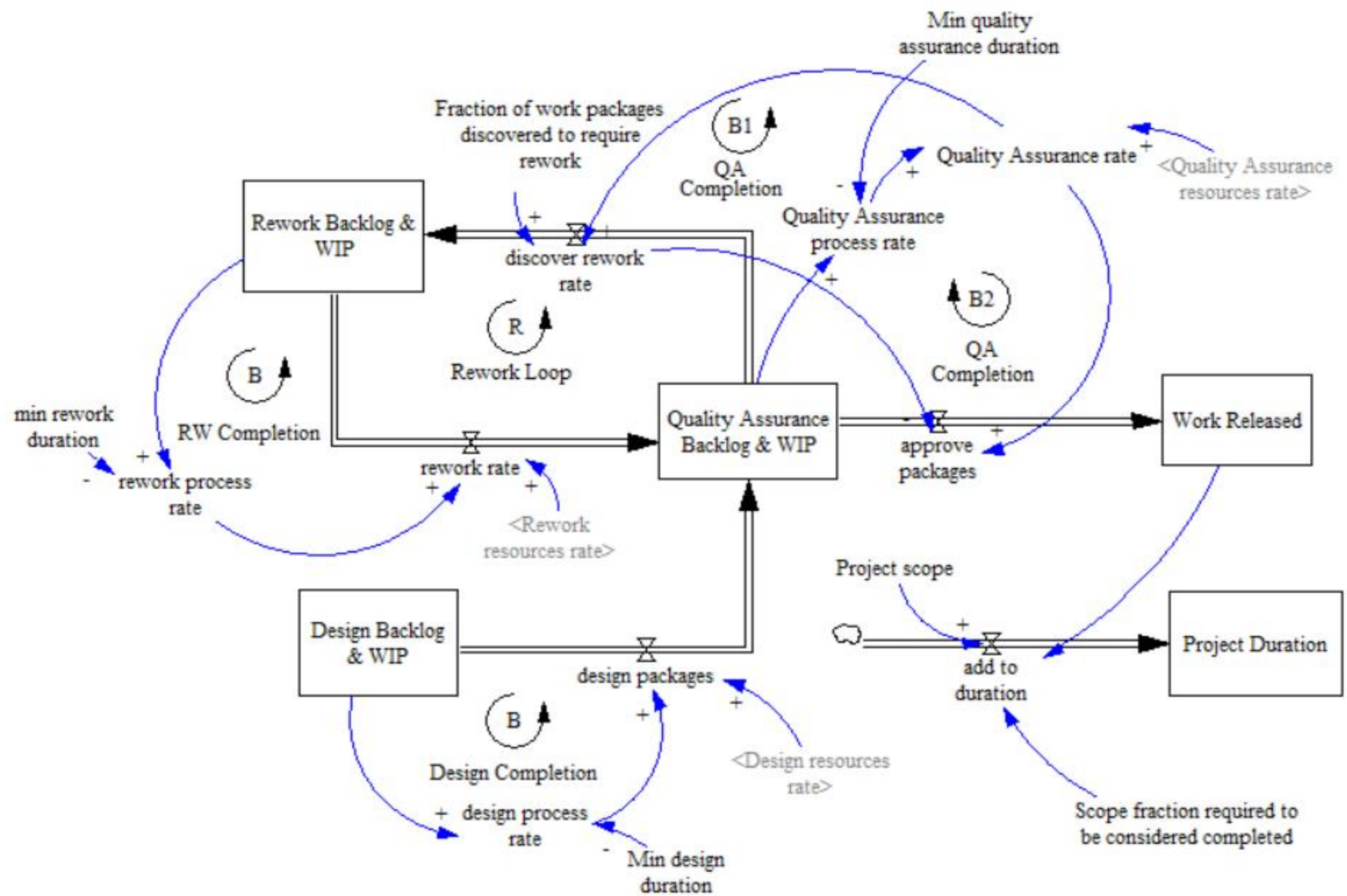


Fig 65: Archetypical Project Model (based on Taylor & Ford, 2006)

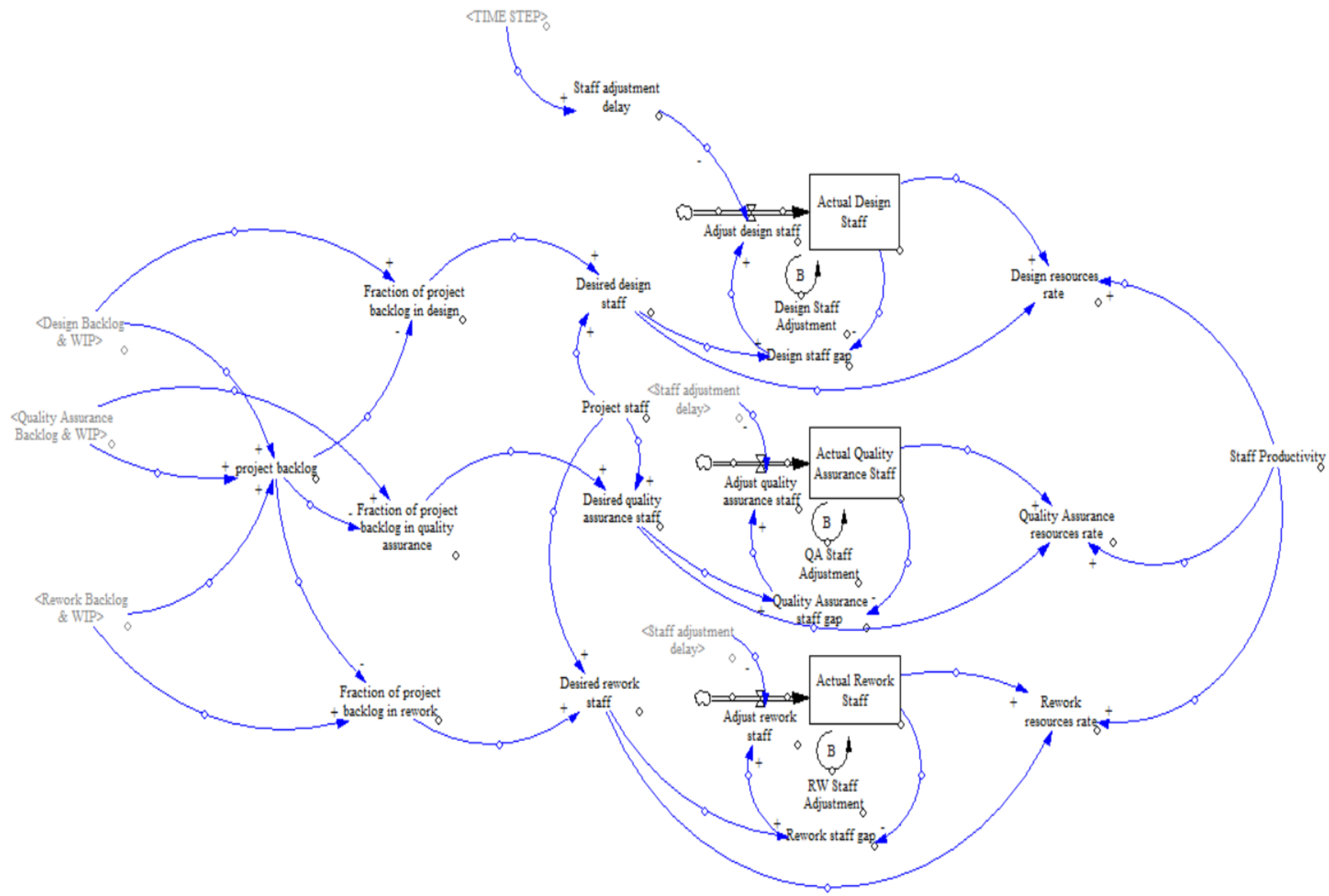


Fig 66: Archetypical Project Model – Resource Allocation (based on Taylor & Ford, 2006)

Documented Model Equations

The equations for the reconstructed model are based on the original project archetypical model built by Taylor & Ford (2006) . The archetypical project model can be accessed by requesting Ford, D.N at DavidFord@tamu.edu for a copy of the same.

The modified model has a few equations different to the archetype as listed below.

1) Design Backlog & WIP = INTEG (-design packages, Project scope)

Units: work packages

Comment: The number of work packages waiting to be constructed.

2) Fraction of work packages discovered to require rework=0.2

Units: Dmnl

Comment: The percentage of work packages that require rework. NOTE- the base case value is 0.2.

Model Validation

Background

The project model is a well-established model which has been validated and used extensively in published literature. A comprehensive explanation of this project model was provided by Ford &Sterman (1998). This project model has further developed and has been used to study the 90% syndrome where projects appear to have slow down progress during its end phase (Ford & Sterman, 2003). strategic management of complex projects (Lyneis et al., 2001), tipping point failure (Taylor & Ford, 2006), Management of tipping point dynamics (Taylor & Ford, 2008) and even to develop project control models (Lyneis et al., 2007). This model has been used to study specific cases such as failure of Limerick nuclear power plant(Taylor & Ford ,2006) as well as entire systems such as highway projects (Ford et al., 2004). Project models have been used extensively in flight simulators created for management training. Prominent firms such as BP, Bath, Ford, Hughes/Raytheon and the World Bank use these flight simulators for training purposes (Lyneis & Ford, 2007) This indicates that this model is applicable over various domains.

Boundary Adequacy

The important concepts addressing capability traps are endogenous to this model, i.e., all components of the rework loop are modeled endogenously. The boundaries of this model are the same as those of archetypical project management model because the reconstructed model used same equations as the archetypical model.

Structure Assessment

The recreated model conforms to the structure of the archetypical project model. While reconstructing the model, sub-models were tested, and they were found to conform to expected behavior.

Dimensional Consistency

The recreated model has been checked for consistency of units. The equations are found to be dimensionally consistent and have real world meaning. This is consistent with the archetypical model.

Parameter Assessment

The source of parametric evaluation for the recreated model is Taylor & Ford's project model (Contact Dr. David Ford at DavidFord@tamu.edu for model). The parameters used in this model have real life meaning as described in the comments.

Extreme Conditions

Model Component	Data Range	Data used in simulation (Base case)	Extreme Values	Behavior	Is this expected behavior?
Fraction of work packages discovered to require rework	[0,1]	0.2	0 & 1	Upon inspection, the QA team discovers errors and requests rework on work packages. If the work is flawless, rework is not required (0) and if the work is totally faulty then all the work packages need to be reworked (1)	Yes
Min design duration	(0,2]	1 Week	2	It is estimated that for a work package to be designed, it takes a minimum of 1 week (base case). In the event new techniques are developed and implemented, this value decreases drastically (however it has to be a non-zero value) and if the existing technology becomes obsolete, this value increases (2). Increasing this increases the overall project duration.	Yes

Table 8: Project Model – Summary of Extreme Conditions Test

Model Component	Data Range	Data used in simulation (Base case)	Extreme Values	Behavior	Is this expected behavior?
Min quality assurance duration	(0,2]	1 Week	2	It is estimated that for a work package to be checked, it takes a minimum of 1 week (base case). In the event new techniques are developed and implemented, this value decreases drastically (however it has to be a non-zero value) and if the work package becomes complex , this value increases (2). Increasing this increases the overall project duration.	Yes
min rework duration	(0,2]	1 Week	2	It is estimated that for a work package to be reworked, it takes a minimum of 1 week (base case). In the event new techniques are developed and implemented, this value decreases drastically (however it has to be a non-zero value) and if the existing technology becomes obsolete, this value increases (2). Increasing this increases the overall project duration.	Yes

Table 8: Continued

Model Component	Data Range	Data used in simulation (Base case)	Extreme Values	Behavior	Is this expected behavior?
Project scope	[0,1000]	500 work Packages	0 & 1000	0 represents a scenario where a project gets dropped. 1000 represents a very large project. Increasing this increases the overall project duration.	Yes
Project staff	(0,50]	20 People	50	This represents the size of the workforce. Increasing the size of workforce decreases the duration of the project.	Yes
Scope fraction required to be considered completed	[0,1]	0.995	0 & 1	0-If the project is dropped. Increasing this variable increases the project duration. Indicates substantial completion.	Yes
Staff Productivity	[0,2]	1	0 & 2	Increasing staff productivity decreases project duration	Yes

Table 8: Continued

The recreated model responds well to extreme conditions and produces reasonable behaviors which are consistent with mental models when simulated under extreme conditions.

Behavior Reproduction

On recreating Taylor & Ford's Project model, it was of paramount importance to verify if the equations used to build it were accurate. The model's behavior for typical conditions is consistent with the archetypical project model. The model is capable of generating the s-shaped curve (as shown in fig 67) for work released over time. This was accomplished this simulating the model under base case conditions.

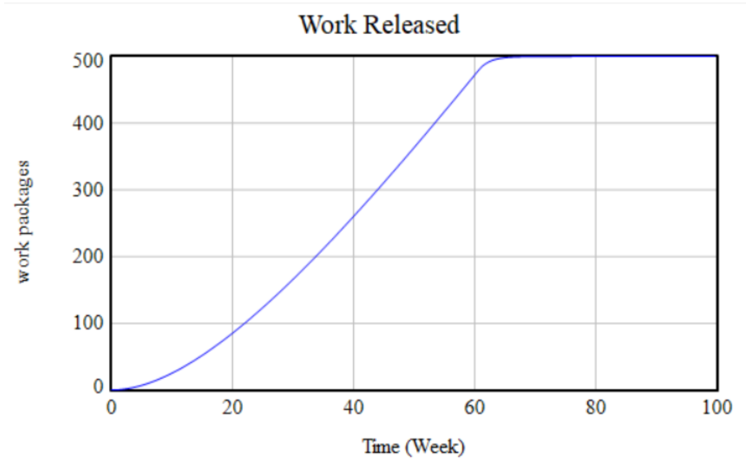


Fig 67: Project Model – work released over time

Behavior Anomaly

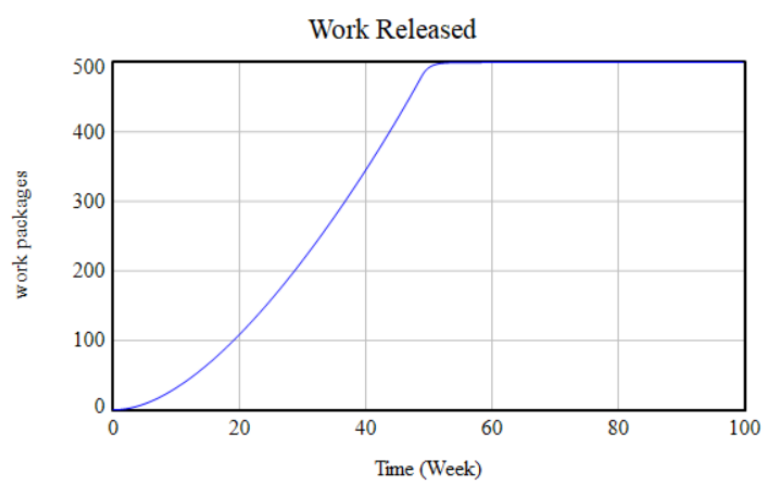


Fig 68: Loop Knockout Test, Project Model

A loop knockout test was administered on the recreated model. The model proved to be robust and have a consistent behavior even when certain loops were made ineffective. Rework loop was made ineffective by setting the fraction of work packages discovered to require rework as zero. The model behaved consistently and was still able to produce the S-shaped curve for work released over time. As expected, the time to complete the project reduces significantly when compared to the base case conditions. The results of this test were consistent with the test performed on the archetypical model.

Integration Error

The results are not very sensitive to time step or numerical integration techniques. The simulation was run for base case parameters. The graph shows the behavior of output over time for time steps equal to 0.03125 Weeks, 0.0625 Weeks, 0.25 Weeks and 1 Week. The difference between these cases are not significant (fig 69), all of them show the same behavior and attain the same equilibrium.

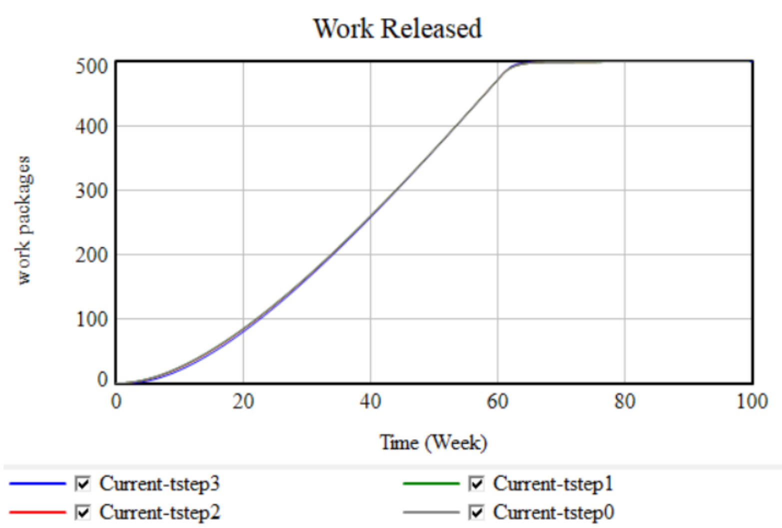


Fig 69: Sensitivity - variation in timestep, Project Model

Surprise Behavior

The model was simulated under various time steps and for different durations. These tests also included varying all the time constants, scope, error fraction and productivity. However, the model behaved consistently. For instance, increasing productivity decreases the project.

Sensitivity Analysis

Univariate sensitivity analysis performed on the reconstructed model replicated the results of the analysis performed on the archetypical project model. Rework fraction, productivity and the project completion definition (Scope fraction required to be considered completed) were found to be high leverage points in this system. The results of this test has been included in the analysis.

Conclusion

Based on the validation tests performed on the recreated model, it can be concluded that the recreated model behaves exactly similar to the original project management archetypical model created by Taylor and Ford.

Model Use

The reconstructed model designed to replicate the archetypical project model by Taylor & Ford. By understanding this model, it is possible to design a realistic project model with capability traps. The model was subjected to sensitivity analysis. This model shall be further used to replicate the capability traps occurring in construction projects by combining it with elements from the archetypical capability traps model.

APPENDIX C

PROJECT CAPABILITY TRAP MODEL: MODEL SUPPORT FILE

General Notes

This document provides evidence to support that the new project capability trap model (P-C Trap model) integrates the capability trap archetype (Lyneis & Sterman ,2016) into the project model (Taylor & Ford, 2006) effectively. This model has been designed using formulae intended to study the effects of capability trap on discrete projects.

While previous capability trap models have proposed that an increase in capability increases productivity thus boosting overall production, we take a closer look at how this happens at construction projects. Capability is dependent on the total amount of improvement effort. There are two ways to look at this proposition of increasing productivity, we propose that increasing improvement effort reduces the errors made on the project. A reduction of errors should reduce rework by a significant amount, boosting the amount of work released. A second way is that improvement effort can often lead to uncovering new techniques or training in new tools. This should cut down the minimum time required to complete a production activity significantly. Both these propositions shall be looked into while developing the new project model.

The Project Capability Trap model has seventeen variables with dimensionless units as shown in table 9. However, all these variables are fractions, related to capabilities or sensitivity parameters. The model has four equations with embedded data as shown in Table 10. However, these parameters were defined in a manner identical to the parent models, i.e., archetypical capability trap model and project model. The model has a supplementary variable to measure the duration of the project. Project Duration is solely a performance measure and is listed as a supplementary variable. The recreated model also had 62 variables without predefined minimum or maximum. This was because minimum and maximum were only defined if necessary, as done in the original models.

Module	Group	Type	Variable
Default	Akhil PC Model	L	Capabilities (Dmnl)
Default	Akhil PC Model	A	Capability deficit fraction (Dmnl)
Default	Akhil PC Model	C	"Fraction discovered to need rework - reference" (Dmnl)
Default	Akhil PC Model	A	Fraction of project backlog in design (Dmnl)
Default	Akhil PC Model	A	Fraction of project backlog in quality assurance (Dmnl)
Default	Akhil PC Model	A	Fraction of project backlog in rework (Dmnl)
Default	Akhil PC Model	A	Fraction of work packages discovered to require rework (Dmnl [0,1])
Default	Akhil PC Model	LI,C	Initial Capabilities (Dmnl)
Default	Akhil PC Model	C	Max fraction discovered to require rework (Dmnl)
Default	Akhil PC Model	C	Maximum Capabilities (Dmnl)
Default	Akhil PC Model	C	Min fraction discovered to require rework (Dmnl)
Default	Akhil PC Model	C	Reference Fraction of Effort to Output (Dmnl [0,1])
Default	Akhil PC Model	C	Scope fraction required to be considered completed (Dmnl [0,1])
Default	Akhil PC Model	C	Sensitivity of Min design duration to Capability Defect (Dmnl)
Default	Akhil PC Model	C	Sensitivity of Min quality assurance duration to Capability Defect (Dmnl)
Default	Akhil PC Model	C	Sensitivity of min rework duration to capability deficity (Dmnl)
Default	Akhil PC Model	C	Sensitivity of rework fraction to capabilities (Dmnl)

Table 9: Project Capability Trap Model - Variables with dimensionless units

Module	Group	Type	*Variable* (4)
Default	Akhil PC Model	A	Average Capability Loss Rate (1/Week)
Default	Akhil PC Model	A	Min design duration (Week [0,2])
Default	Akhil PC Model	A	Min quality assurance duration (Week [0,2])
Default	Akhil PC Model	A	min rework duration (Week [0,2])

Table 10: Project Capability Trap Model – Equations with embedded data.

Assumptions: The recreated model assumes that the project scope, staff productivity and the number of workers allotted to the project remain constant.

This model has the following differences from difference from the archetypical project model (Appendix B):

- The model has an additional stock representing capability and additional flows representing increase and decrease of capability. Additional auxiliary variables such as capability delay order, maximum capability, etc. are included in this model. This structure is similar to the capability trap archetypical model.
- Capability deficit fraction is defined as the ratio of difference between the initial capabilities and current capabilities to initial capabilities.
- Fraction of work packages discovered to require rework is no longer modelled as a constant but as a function of capability deficit fraction.
- Rework Fraction is sensitive to capabilities.
- The minimum amount of time required to complete production activities (Design, QA & Rework) is not a constant. The minimum amount of time required to complete production activities are sensitive to capabilities.
- The workers are distributed among four activities, i.e., Design, Quality Assurance, Rework and Capability Development. The archetypical project model did not consider capability development. The distribution of workers among capability staff and production staff can be controlled by varying the Fraction of Workforce to Production Effort.
- Resource rate has been redefined as the total work effort (Staff *work effort) times productivity of the work effort.
- Effort rate is the amount of time spent in terms workweeks. One workweek is equivalent to 40 hours/week. Effort rate is defined separately for production activities and capability development.

- Productivity of improvement effort is defined as the increase in capabilities per week of improvement effort. It is set so that the simulations begin in equilibrium along the lines of capability trap archetypical model.
- A new set of equations intended to capture the steady state progress rate are added.

Formal Model Structure

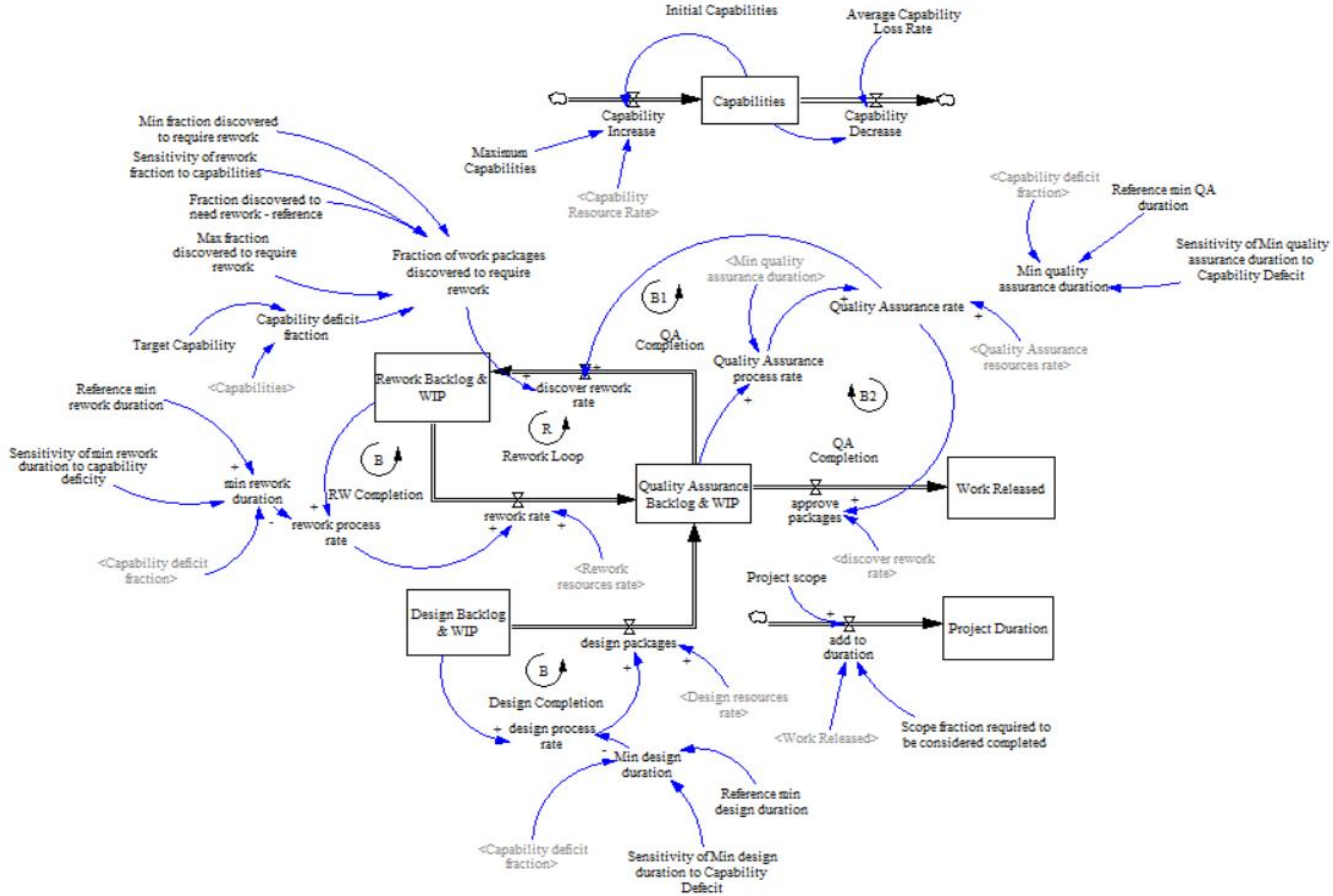


Fig 70: Project Capability Trap Model

The formal model integrates the archetypical capability trap model with a basic version of the project model, and it has additional components as shown in figures 70, 71 and 72. This model is largely based on basic project model described in Appendix B. Capability is modelled to influence the rework fraction and the minimum process durations as shown in Fig 70. The conceptual model is the aggregation of the conceptual models described in appendix A and appendix 70. It can be observed that the rework loop is already an existing work harder loop. By adding the capability trap layer, we introduce a work smarter loop. It can be noticed that in figure 70, capability deficit fraction affects the minimum duration of all activities and the error fraction. Capability deficit fraction is a function of capabilities and by tracing this component through the model, we can observe a work smarter loop.

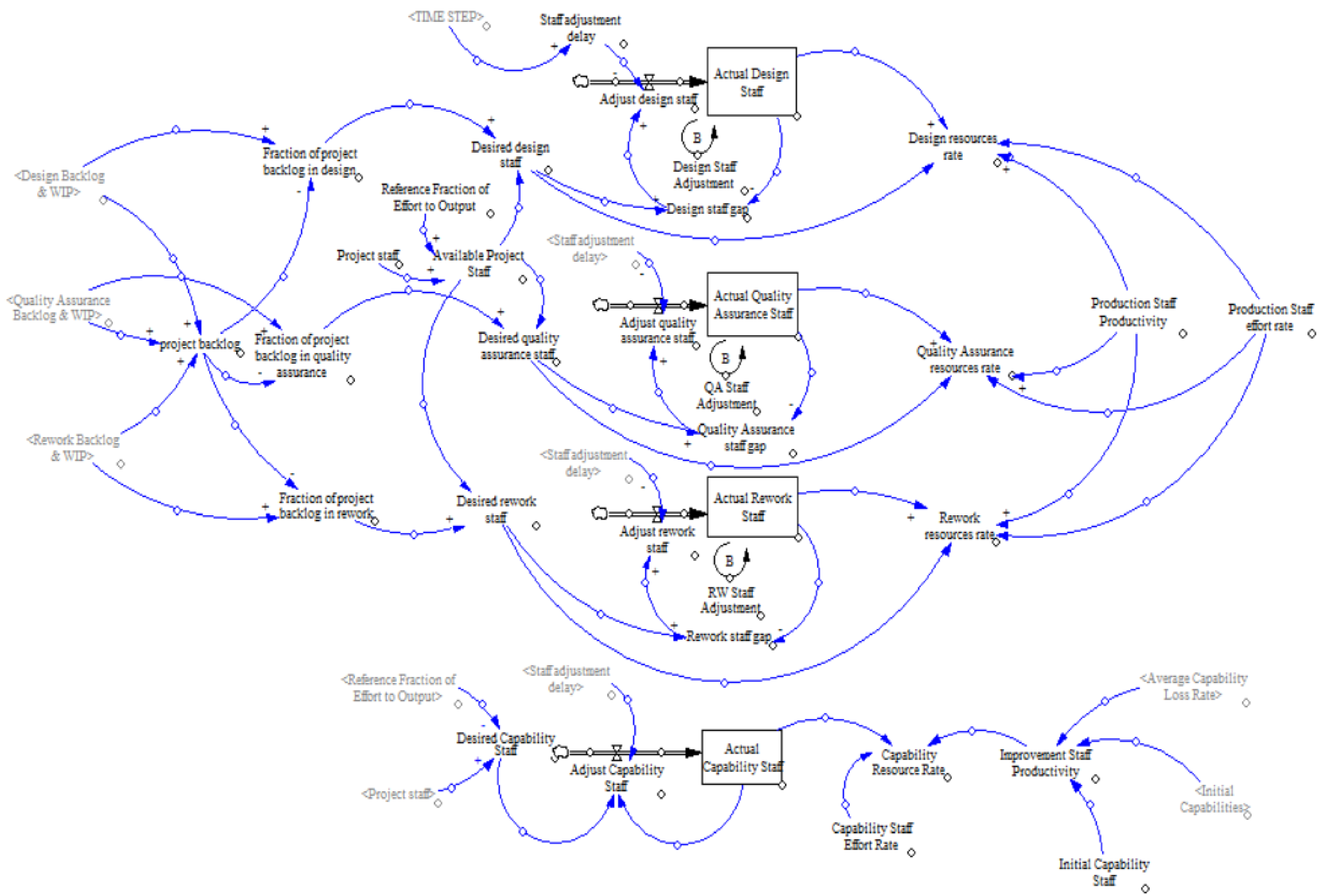


Fig 71: Project Capability Trap Model – Resource Allocation

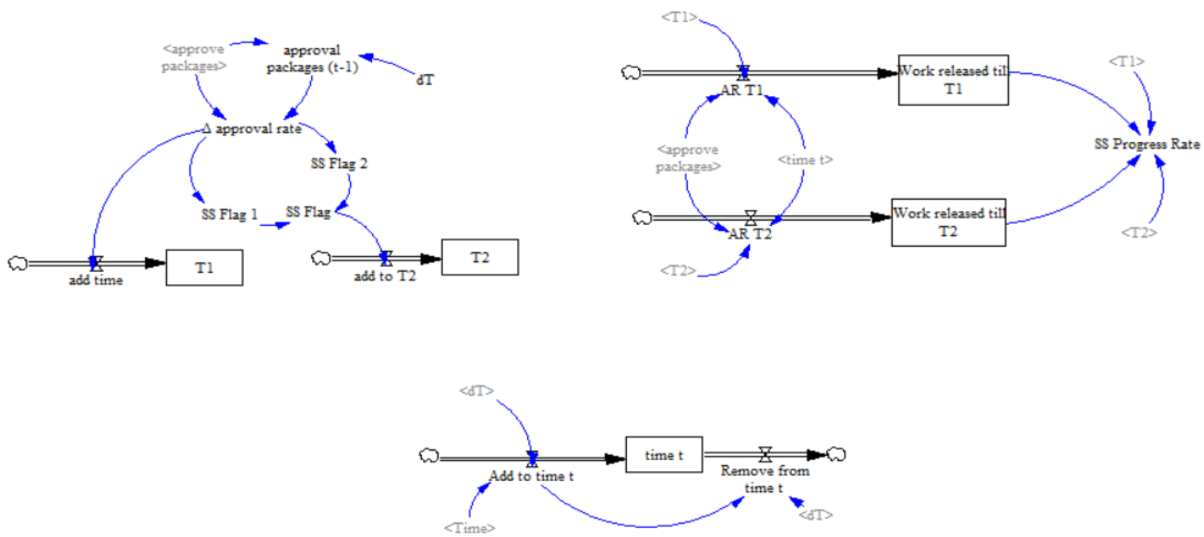


Fig 72: Project Capability Trap Model – Performance Measure

Documented Model Equations

(01) Actual Capability Staff= INTEG (Adjust Capability Staff, Initial Capability Staff)

Units: person

The capability development staff that is currently in place on the project.

(02) "approval packages (t-1)"=DELAY FIXED(approve packages, dT , approve packages)

Units: work packages/Week

Records the rate of work approval at time, t-1.

(03) Actual Design Staff= INTEG (Adjust design staff, Project staff)

Units: person

The design staff that is currently in place on the project. The initial condition indicates that at the beginning of the entire project staff is assigned to design.

(04) Actual Quality Assurance Staff= INTEG (Adjust quality assurance staff, 0)

Units: person

The quality assurance staff that is currently in place on the project.

(05) Actual Rework Staff= INTEG (Adjust rework staff, 0)

Units: person

The rework staff that is currently in place on the project.

(06) add time=IF THEN ELSE(Δ approval rate>0.4, 1 , 0)

Units: Week/Week

Used to capture the value of T_1, i.e., duration till end of startup phase.

(07) add to duration=IF THEN ELSE(Work Released<Scope fraction required to be considered completed * Project scope, 1 , 0)

Units: Week/Week

Adds to the project duration if the amount of work released is less than the work required to be completed before the project can be considered complete.

(08) add to T2=IF THEN ELSE(SS Flag=1, 1 , 0)

Units: Week/Week

Used to capture the value of T_1, i.e., duration elapsed till start of closeout phase.

(09) Add to time t= Time/dT

Units: Week/Week

Used to model time as a different variable.

(10) Adjust Capability Staff= ((Desired Capability Staff-Actual Capability Staff)/Staff adjustment delay)

Units: person/Week

Adjusts the capability staff on the project. The adjustment is assumed to occur over the staff delay time.

(11) Adjust design staff= (Design staff gap/Staff adjustment delay)

Units: person/Week

Adjusts the design staff on the project. The adjustment is assumed to occur over the staff delay time. If the design staff gap is negative the actual design staff is reduced.

(12) Adjust quality assurance staff= Quality Assurance staff gap/Staff adjustment delay

Units: person/Week

Adjusts the quality assurance staff on the project. The adjustment is assumed to occur over the staff delay time. If the quality assurance staff gap is negative the actual quality assurance staff is reduced.

(13) Adjust rework staff= (Rework staff gap/Staff adjustment delay)

Units: person/Week

Adjusts the rework staff on the project. The adjustment is assumed to occur over the staff delay time. If the rework staff gap is negative the actual rework staff is reduced.

(14) approve packages= Quality Assurance rate-discover rework rate

Units: work packages/Week

The rate at which work packages are approved and released. It is the difference between the quality assurance rate and the rate at which work packages are discovered to require rework.

(15) AR T1= IF THEN ELSE(ABS(T_1-time t)<1, approve packages, 0)

Units: work packages/Week

Rate of work released till T_1.

(16) AR T2= IF THEN ELSE(ABS(T_2-time t)<1, approve packages, 0)

Units: work packages/Week

Rate of work released till T_2.

(17) Available Project Staff= Project staff*Fraction of Workforce to Production Effort

Units: person

The number of people available for production activities (Design, QA & rework)

(18) Average Capability Loss Rate= 1/104

Units: 1/Week

The fractional rate at which capabilities erode as personnel turn over and as environmental, technological, competitive and other conditions change. The value of 0.5/year in the original model was changed to 1/104 percent per week in the project model.

(19) Capabilities= INTEG (Capability Increase-Capability Decrease, Initial Capabilities)

Units: Dmnl

The capabilities of the project team are a stock, increased by improvement effort and investment in capability development, and decreased as capabilities erode.

(20) Capability Decrease= Capabilities*Average Capability Loss Rate

Units: 1/Week

Capabilities erode over time after a certain delay, with a mean Lag given by the reciprocal of the fractional capability erosion rate. Capability erosion is modeled as an Erlang lag. The user can specify the order of the delay.

(21) Capability deficit fraction= ZIDZ((Target Capability-Capabilities), Target Capability)

Units: Dmnl

The deficit of capabilities relative to the normal amount of capabilities, as a fraction. Values >1 reflect "surplus" capabilities. (0, max capabilities=10)

(22) Capability Increase= Capability Resource Rate*(Maximum Capabilities-Capabilities)/Maximum Capabilities

Units: 1/Week

Capabilities increase as the result of effort applied to improvement effort and capability development. Improvement is determined by the product of the labor force, the average time per person per week spent on improvement and the productivity of improvement effort. Improvement slows, however, as capabilities approach their maximum value. Capabilities can increase with education and training.

(23) Capability Resource Rate=Actual Capability Staff*Improvement Staff Productivity*Capability Staff Effort Rate

Units: 1/Week

Capability resource rate captures the total effort put in by the project team towards capability development. It is the product of the total number of staff working towards capability development, the work effort (in hours or weeks) and the productivity of the improvement effort.

(24) Capability Staff Effort Rate= 1

Units: Week/Week

The time spent on capability development and improvement. The amount of work put in by capability staff per week. (1 workweek is equivalent to 40 hours of work/ week ,i.e., 40 hours/week = 1 week/week)

(25) "Design Backlog & WIP"= INTEG (-design packages, Project scope)

Units: work packages

The number of work packages waiting to be constructed.

(26) design packages=MIN(design process rate, Design resources rate)

Units: work packages/Week

The rate at which work packages are constructed can be constrained by either available resources or available work packages. The minimum rate between available work and available resources determines the rate at which packages are constructed.

(27) design process rate= "Design Backlog & WIP"/Min design duration

Units: work packages/Week

The number of work packages that can be designed if the process constrains the rate. It assumes that work is available after it has remained in the design backlog for the minimum duration.

(28) Design resources rate=((0*Desired design staff*Production Staff Productivity)+(1*Actual Design Staff *Production Staff Productivity))*Production Staff effort rate

Units: work packages/Week

The rate at which packages can be designed when constrained by resources. It increases with increases in design staff and staff productivity.

(29) Design staff gap= Desired design staff-Actual Design Staff

Units: person

The difference between the desired design staff and the actual design staff. The actual design staff approaches the desired level over through the 1st order delay. If the desired design staff is less than the actual design staff the gap is negative and the actual design staff decreases after a delay.

(30) Desired Capability Staff= Project staff*(1-Fraction of Workforce to Production Effort)

Units: person

The desired number of persons to be assigned to the capability development staff based upon the Fraction of Workforce to Production Effort. The smaller the fraction, more project staff are assigned to the capability development team and vice versa.

(31) Desired design staff= Fraction of project backlog in design*Available Project Staff

Units: person

The desired number of persons to be assigned to the design staff based upon the proportion of design work to the project backlog.

(32) Desired quality assurance staff= Fraction of project backlog in quality assurance*Available Project Staff

Units: person

The desired number of persons to be assigned to the quality assurance staff based upon the proportion of quality assurance work to the project backlog.

(33) Desired rework staff= Fraction of project backlog in rework*Available Project Staff

Units: person

The desired number of persons to be assigned to the rework staff based upon the proportion of rework backlog to the project backlog.

(34) discover rework rate= Fraction of work packages discovered to require rework*Quality Assurance rate

Units: work packages/Week

The rate at which work packages are discovered to require rework. The rate increases with both the quality assurance rate and the percentage of tasks that require rework.

(35) dT= 1

Units: Week

Used to generate a time difference of 1 week to capture T_1 & T_2.

(36) FINAL TIME = 200

Units: Week

The final time for the simulation.

(37) "Fraction discovered to need rework - reference"= 0.2

Units: Dmnl

The fraction of work discovered to require rework that occurs regardless of the capabilities of the staff, i.e. the rework fraction if the staff has the reference (target) capabilities.

(38) Fraction of project backlog in design= "Design Backlog & WIP"/project backlog

Units: Dmnl

The percentage of work packages that are contained within the design backlog. It increases as the design backlog increases and decreases as the project backlog increases.

(39) Fraction of project backlog in quality assurance="Quality Assurance Backlog & WIP"/project backlog

Units: Dmnl

The percentage of work packages that are contained within the quality assurance backlog. It increases as the quality assurance backlog increases and decreases as the project backlog increases.

(40) Fraction of project backlog in rework= "Rework Backlog & WIP"/project backlog

Units: Dmnl

The percentage of work packages that are contained within the quality assurance backlog. It increases as the quality assurance backlog increases and decreases as the project backlog increases.

(41) Fraction of work packages discovered to require rework= MAX (Min fraction discovered to require rework, MIN(Max fraction discovered to require rework, "Fraction discovered to need rework - refence"*(1+Capability deficit fraction*Sensitivity of rework fraction to capabilities)))

Units: Dmnl [0,1]

The percentage of work packages that are discovered to require rework increases from the reference value generated due to complexity, etc. based on the size of the capabilities gap and is limited to 1.00, when all work is flawed.

(42) Fraction of Workforce to Production Effort= IF THEN ELSE(Time<100, 1 , 0.8)

Units: Dmnl [0,1]

The fraction of the workforce devoted to production activities. The remainder is devoted to improvement and investment in capabilities. Base Case = 0.95 (1 worker to capability development)

(43) Improvement Staff Productivity=Initial Capabilities*Average Capability Loss Rate/Initial Capability Staff

Units: 1/person/Week

The productivity of improvement effort is the increase in capabilities per week of improvement effort. It is set so that the simulations begin in equilibrium along the lines of capability trap archetypical model. It is also defined as a constant to be consistent with the archetypical project model which assumes productivity to be constant.

(44) Initial Capabilities= 100

Units: Dmnl

The starting number of capabilities needed to perform the work at reference rework fraction.

(45) Initial Capability Staff= 1

Units: person

The size of the initial capability staff at t=0.

(46) INITIAL TIME = 0

Units: Week

The initial time for the simulation.

(47) Max fraction discovered to require rework= 1

Units: Dmnl

The maximum fraction of rework that can be generated and discovered. Assumes the staff does some things right even when capabilities are never developed and are at a minimum.

(48) Maximum Capabilities= 1000

Units: Dmnl

The maximum level of capabilities determined by the project manager.

(49) Min design duration= Reference min design duration*(1+(max(-0.9, (Capability deficit fraction* Sensitivity of Min design duration to Capability Deficit))))

Units: Week [0,2]

The minimum number of weeks a work packages must stay in the design backlog until it can be constructed. Accounting for deployment of new technology/best practices.

(50) Min fraction discovered to require rework= 0

Units: Dmnl

The minimum fraction of rework that can be generated and discovered.

(51) Min quality assurance duration= Reference min QA duration*(1+(max(-0.9, (Capability deficit fraction*Sensitivity of Min quality assurance duration to Capability Deficit))))

Units: Week [0,2]

The minimum number of weeks a work packages must stay in the quality assurance backlog until it can be checked for errors- accounts for implementing best practices ,new checks, etc.

(52) min rework duration= Reference min rework duration*(1+(max(-0.9, (Capability deficit fraction * Sensitivity of min rework duration to capability deficit))))

Units: Week [0,2]

The minimum number of weeks a work packages must stay in the rework backlog until it can be reworked.

(53) Production Staff effort rate= 1

Units: Week/Week

The time spent on production activities (Design, QA & Rework). The amount of work put in by production staff per week. (1 workweek is equivalent to 40 hours of work/ week, i.e., 40 hours/week = 1 week/week)

(54) Production Staff Productivity= 1

Units: work packages/(person*Week) [0,?]

The number of work packages that a person can complete in a week. The current formulation assumes that staff productivity is constant through the project and across activities.

(55) project backlog="Design Backlog & WIP"+ "Quality Assurance Backlog & WIP"+ "Rework Backlog & WIP"

Units: work packages

The project backlog represents the work packages remaining to be completed on the project. It is the sum of the Design, QA, and RW backlogs.

(56) Project Duration= INTEG (add to duration,0)

Units: Week

The weeks required to complete the project based upon the percent of work required for the project to be considered complete and the amount of work completed to date.

(57) Project scope=500

Units: work packages [0,1000]

The number of work packages that must be completed and approved to complete the project. Each work packages represents a small piece of the project. NOTE: the base case value is 500 work packages.

(58) Project staff= 20

Units: person [0,50]

The number of people assigned to the project.

(59) "Quality Assurance Backlog & WIP"= INTEG (design packages+ rework rate-approve packages-discover rework rate,0)

Units: work packages

The number of work packages waiting to be checked for quality assurance.

(60) Quality Assurance process rate="Quality Assurance Backlog & WIP"/Min quality assurance duration

Units: work packages/Week

The number of work packages that can be checked for errors if the process constrains the rate. It assumes that work is available after it has remained in the quality assurance backlog for the minimum duration.

(61) Quality Assurance rate=MIN(Quality Assurance process rate, Quality Assurance resources rate)

Units: work packages/Week

The rate at which work packages are checked for errors can be constrained by either available resources or available work packages. The minimum rate between available work and available resources determines the rate at which packages are checked for errors.

(62) Quality Assurance resources rate= ((0*Desired quality assurance staff*Production Staff Productivity)+(1*Actual Quality Assurance Staff*Production Staff Productivity))*Production Staff effort rate

Units: work packages/Week

The rate at which packages can be checked for errors when constrained by resources. It increases with increases in quality assurance staff and staff productivity.

(63) Quality Assurance staff gap= Desired quality assurance staff-Actual Quality Assurance Staff

Units: person

The difference between the desired quality assurance staff and the actual quality assurance staff. The actual quality assurance staff approaches the desired level over through the 1st order delay. If the desired quality assurance staff is less than the actual quality assurance staff the gap is negative and the actual quality assurance staff decreases after a delay.

(64) Reference min design duration= 10

Units: Week

The minimum number of weeks a work packages must stay in the design backlog until it can be constructed.

(65) Reference min QA duration= 10

Units: Week

The minimum number of weeks a work packages must stay in the quality assurance backlog until it can be checked for errors.

(66) Reference min rework duration= 10

Units: Week

The minimum number of weeks a work packages must stay in the rework backlog until it can be reworked.

(67) Remove from time t= DELAY FIXED(Add to time t, dT , 0)

Units: Week/Week

Outflow used to capture simulation time.

(68) "Rework Backlog & WIP"= INTEG (discover rework rate-rework rate, 0)

Units: work packages

The number of work packages that are waiting to be reworked.

(69) rework process rate= "Rework Backlog & WIP"/min rework duration

Units: work packages/Week

The number of work packages that can be reworked if the process constrains the rate. It assumes that work is available after it has remained in the rework backlog for the minimum duration.

(70) rework rate= MIN(rework process rate, Rework resources rate)

Units: work packages/Week

The rate at which work packages are reworked can be constrained by either available resources or available work packages. The minimum rate between available work and available resources determines the rate at which packages are reworked.

(71) Rework resources rate=((0*Desired rework staff*Production Staff Productivity)+(1*Actual Rework Staff *Production Staff Productivity))*Production Staff effort rate

Units: work packages/Week

The rate at which packages can be reworked when constrained by resources. It increases with increases in rework staff and staff productivity.

(72) Rework staff gap=Desired rework staff-Actual Rework Staff

Units: person

The difference between the desired rework staff and the actual rework staff. The actual rework staff approaches the desired level over through the 1st order delay. If the desired rework staff is less than the actual rework staff the gap is negative and the actual rework staff decreases after a delay.

(73) SAVEPER = TIME STEP

Units: Week [0,?]

The frequency with which output is stored.

(74) Scope fraction required to be considered completed=0.995

Units: Dmnl [0,1]

The percentage of initial scope that must be complete for the project to be considered complete.

(75) Sensitivity of Min design duration to Capability Deficit=1

Units: Dmnl

The amount of influence that deficit/ surplus of capabilities have on the minimum design duration

(76) Sensitivity of Min quality assurance duration to Capability Deficit=1

Units: Dmnl

The amount of influence that lack/surplus of capabilities have on the minimum QA duration

(77) Sensitivity of min rework duration to capability deficit=1

Units: Dmnl

The amount of influence that surplus/ deficit of capabilities have on the minimum rework duration

(78) Sensitivity of rework fraction to capabilities = 5

Units: Dmnl

The amount of influence that capabilities have on the rework fraction, reflected in the number of percent that the rework fraction increases for each unit capability deficit.

(79) SS Flag= IF THEN ELSE(SS Flag 1 =1 :OR: SS Flag 2 =1, 1 , 0)

Units: Dmnl

Steady state flag used to integrate elements captured by SS Flags 1&2.

(80) SS Flag 1= IF THEN ELSE(Δ approval rate>0, 1 , 0)

Units: Dmnl

Flag function used to capture the positive portion of Δ approval rate while computing T_2.

(81) SS Flag 2= IF THEN ELSE(Δ approval rate<-0.2, 1 , 0)

Units: Dmnl

Flag function used to capture the negative portion of Δ approval rate while computing T_2.

(82) SS Progress Rate= ZIDZ((Work released till T2-Work released till T1) , (T2-T1))

Units: work packages/Week

Steady State progress rate is the linear approximation of work released weekly between startup and close out phases of the project.

(83) Staff adjustment delay= TIME STEP

Units: Week

The time required for a person to move from one activity to a different activity. The delay represents the assumption that a worker cannot instantly move from one activity to another but rather gradually decreases their effort on the "old" activity while simultaneously increasing their effort on the "new" activity. For simplicity the model is initially calibrated with the smallest possible delay (TIME STEP) to simulate no delay.

(84) T1= INTEG (add time,0)

Units: Week

Time elapsed till the end of startup phase.

(85) T2= INTEG (add to T2,0)

Units: Week

Time elapsed till the beginning of closeout phase.

(86) Target Capability=100

Units: Dmnl

The number of capabilities required to complete the project.

(87) TIME STEP = 0.03125

Units: Week [0,?]

The time step for the simulation.

(88) time t= INTEG (Add to time t-Remove from time t, 0)

Units: Week

Captures the simulation time as a separate stock variable.

(89) Work Released= INTEG (approve packages, 0)

Units: work packages

The number of work packages that have been completed.

(90) Work released till T1= INTEG (AR T1, 0)

Units: work packages

Work released in the startup phase of the project.

(91) Work released till T2= INTEG (AR T2, 0)

Units: work packages

Work released before the closeout phase of the project.

(92) Δ approval rate= approve packages-"approval packages (t-1)"

Units: work packages/Week

Change in approval rate.

Model Validation

Boundary Adequacy

The important concepts addressing capability traps are endogenous to this model, i.e., all components of the rework loop are modeled endogenously. All the elements used in the project model (appendix ii) have also been used here.

Endogenous	Exogenous	Excluded
Design Backlog & WIP	Average Capability Loss Rate	
QA Backlog & WIP	Capability Delay Order	
Rework Backlog & WIP	Capability Staff Effort Rate	
Work Released	Fraction discovered to need rework - reference	
Project Duration	Initial Capabilities	
Actual Capability Staff	Initial Capability Staff	
Actual Design Staff	Max fraction discovered to require rework	
Actual Quality Assurance	Maximum Capabilities	
Actual Rework Staff	Min fraction discovered to require rework	

Table 11: Project Capability Trap Model – Boundary Adequacy

Endogenous	**Exogenous**	**Excluded**
Capabilities	Production Staff effort rate	
Capability Decrease	Production Staff Productivity	
Capability deficit fraction	Project scope	
add to duration	Project staff	
Adjust Capability Staff	Fraction of Workforce to Production Effort	
Adjust design staff	Reference min design duration	
Adjust quality assurance staff	Reference min QA duration	
Adjust rework staff	Reference min rework duration	
Adjust rework staff	Scope fraction required to be considered completed	
Available Project Staff	Sensitivity of Min design duration to Capability Deficit	
Capability Increase	Sensitivity of Min quality assurance duration to Capability Deficit	
Capability Resource Rate	Sensitivity of min rework duration to capability deficit	
design process rate	Sensitivity of rework fraction to capabilities	
Design resources rate	Target Capability	
Design staff gap		
Desired Capability Staff		
Desired design staff		
Desired quality assurance staff		
Desired rework staff		
discover rework rate		

Table 11: Continued

Endogenous	**Exogenous**	**Excluded**
Fraction of project backlog in design		
Fraction of project backlog in quality assurance		
Fraction of project backlog in rework		
Fraction of work packages discovered to require rework		
Improvement Staff Productivity		
Min design duration		
Min quality assurance duration		
min rework duration		
project backlog		
Project Duration		
Quality Assurance process rate		
Quality Assurance rate		
Quality Assurance resources rate		
Quality Assurance staff gap		
rework process rate		
rework rate		
Rework resources rate		
Rework staff gap		
Staff adjustment delay		
Work Released		

Table 11: Continued

Structure Assessment

While reconstructing the model, sub-models were tested, and they were found to conform to expected behavior. The results of the structural assessment can be found in the SDM-DOC file attachment.

Dimensional Consistency

This model mainly uses variables from its parent models, i.e., the project model and the capability trap archetypical model. A few additional variables have been used to form a proper interface between the project model and the layer of capability trap archetype. The recreated model has been checked for consistency of units. The equations are found to be dimensionally consistent and have real world meaning. The model passes unit check on the simulation software.

Parameter Assessment

The parameters used in this model are largely based out of its parent models, i.e., the capability trap archetype (appendix i) and the project model (appendix ii). However, a few additional variables have also been introduced to create an interface between these two exiting models. In addition to this, the base case values of some variables used to describe previous models have been varied. We shall be looking exclusively at these parameters for this test. The parameters used in this model have real life meaning as described in the comments.

Parameter Name	Parameter type	Min Value	Max Value	Base Case	Comments
Actual Capability Staff	Endogenous	0	Project Staff		Stock representing the size of capability staff
Actual Design Staff	Endogenous	0	Project Staff		Stock representing the size of Design staff
Actual Quality Assurance	Endogenous	0	Project Staff		Stock representing the size of QA staff

Table 12: Project Capability Trap Model –Parameter Assessment

Parameter Name	Parameter type	Min Value	Max Value	Base Case	Comments
Actual Rework Staff	Endogenous	0	Project Staff		Stock representing the size of Rework staff
Available Project Staff	Endogenous	0	Project Staff		The total size of Project staff available for production activities.
Capability Resource Rate	Endogenous	0			Capability resource rate captures the total effort put in by the project team towards capability development.
Improvement Staff Productivity	Endogenous	0			The productivity of improvement effort is the increase in capabilities per week of improvement effort.
Capability Staff Effort Rate	Exogenous	0		1	The time spent on capability development and improvement – the amount of work put in by capability staff per week.
Fraction discovered to need rework - reference	Exogenous	0	1	0.2	The fraction of work discovered to require rework that occurs regardless of the capabilities of the staff. This is modelled as a reference value which is subject to change based on capability deficit fraction.
Initial Capability Staff	Exogenous	0	Project Staff	1 Person	The size of the initial capability staff at t=0.
Max fraction discovered to require rework	Exogenous	1	1	1	The maximum fraction of rework that can be generated and discovered.
Min fraction discovered to require rework	Exogenous	0	0	0	The minimum fraction of rework that can be generated and discovered.

Table 12: Continued

Parameter Name	Parameter type	Min Value	Max Value	Base Case	Comments
Production Staff effort rate	Exogenous	0		1	The time spent on production activities (Design, QA & Rework)- The amount of work put in by production staff per week.
Production Staff Productivity	Exogenous	0			The number of work packages that a person can complete in a week.
Fraction of Workforce to Production Effort	Exogenous	0	1	$0.9\overline{4}$	The fraction of the workforce devoted to production activities. Calibrated such that the system starts in equilibrium.
Capability deficit fraction	Endogenous		1		The deficit of capabilities relative to the normal amount of capabilities, as a fraction. Capability deficit fraction of 1 represents a case where the team has no capability to proceed with the project. A negative value of this fraction represents surplus capabilities.
Sensitivity of Min design duration to Capability Deficit	Exogenous	0	1	1	The amount of influence that deficit/ surplus of capabilities have on the minimum design duration.
Sensitivity of Min quality assurance duration to Capability Deficit	Exogenous	0	1	1	The amount of influence that deficit/ surplus of capabilities have on the minimum QA duration. 0 represents a case where progress is not dependent on capability of the project team and 100 represents a case where progress is very sensitive to changes in capability deficit.

Table 12: Continued

Parameter Name	Parameter type	Min Value	Max Value	Base Case	Comments
Sensitivity of min rework duration to capability deficit	Exogenous	0	1	1	The amount of influence that surplus/ deficit of capabilities have on the minimum rework duration.
Sensitivity of rework fraction to capabilities	Exogenous	0	1	1	The amount of influence that capabilities have on the rework fraction, reflected in the number of percent that the rework fraction increases for each unit capability deficit.
Target Capability	Exogenous	0	Maximum Capabilities	100	The number of capabilities required to complete the project. 0 represents no project and when target capabilities is equal to maximum capabilities, it represents a complex project with lots of work packages.

Table 12: Continued

Extreme Conditions

Model Component	Data Range	Data used in simulation (Base case)	Extreme Values	Behavior	Is this expected behavior?
Fraction of work packages discovered to need rework - reference	[0,1]	0.2	0 & 1	Upon inspection, the QA team discovers errors and requests rework on work packages. If the work is flawless, rework is not required (0) and if the work is totally faulty then all the work packages need to be reworked (1). This is only a reference value.	Yes

Table 13: Project Capability Trap Model –Extreme Conditions

Model Component	Data Range	Data used in simulation (Base case)	Extreme Values	Behavior	Is this expected behavior?
Min design duration	(1,20)	10 Weeks	2	It is estimated that for a work package to be designed, it takes a minimum of 10 weeks (base case). In the event new techniques are developed and implemented, this value decreases drastically (however it has to be a non-zero value) and if the existing technology becomes obsolete, this value increases (2). Increasing this increases the overall project duration.	Yes
Min quality assurance duration	(0,20)	10 Weeks	2	It is estimated that for a work package to be checked, it takes a minimum of 10 weeks (base case). In the event new techniques are developed and implemented, this value decreases drastically (however it has to be a non-zero value) and if the work package becomes complex , this value increases (2). Increasing this increases the overall project duration.	Yes
min rework duration	(0,20)	10 Weeks	2	It is estimated that for a work package to be reworked, it takes a minimum of 10 weeks (base case). In the event new techniques are developed and implemented, this value decreases drastically (however it has to be a non-zero value) and if the existing technology becomes obsolete, this value increases (2). Increasing this increases the overall project duration.	Yes

Table 13: Continued

Model Component	Data Range	Data used in simulation (Base case)	Extreme Values	Behavior	Is this expected behavior?
Project scope	[0,1000]	500 work Packages	0 & 1000	0 represents a scenario where a project gets dropped. 1000 represents a very large project. Increasing this increases the overall project duration.	Yes
Project staff	(0,50]	20 People	50	This represents the size of the workforce. Increasing the size of workforce decreases the duration of the project. At 0 people, work does not pass through the system.	Yes
Production Staff Productivity	[0,2]	1	0 & 2	Increasing staff productivity decreases project duration. At a productivity of 0, no work gets approved.	Yes
Average Capability Loss Rate	(0,1)	1/104 per week	0 & 1	This fraction represents the capability lost per week. At a value of 0, no capability is lost, and the work gets processed at a faster rate. For a value of 1, the capability of the system deplete very quickly and the progress halts.	Yes
Capability Staff Effort Rate	[0,2]	1	0 & 2	The time spent on capability development and improvement. At an effort rate of 0, the capabilities diminish very quickly, and the progress rate drops. The steady state progress rate increases with an increase in this parameter	Yes
Production Staff effort rate	[0,2]	1	0 & 2	The time spent on production activities (Design, QA & Rework). At an effort rate of 0, the work halts, and the progress rate drops to zero instantaneously. The steady state progress rate increases with an increase in this parameter	Yes

Table 13: Continued

Model Component	Data Range	Data used in simulation (Base case)	Extreme Values	Behavior	Is this expected behavior?
Target Capability	(0,1000)	100	0 & 1000	The number of capabilities required to complete the project. As this parameter increases, the capability deficit fraction increases, slowing down process rates and increasing the rework fraction, thus decreasing the progress rate significantly.	Yes
Fraction of Workforce to Production Effort	(0,1)	0.944	0 & 1	This represents the fraction of the workforce devoted to production activities. At a value of 0, the work halts instantaneously. At a value of 1, the capabilities diminish over time and the progress rate slows down drastically.	Yes

Table 13: Continued

The recreated model responds well to extreme conditions and produces reasonable behaviors which are consistent with mental models when simulated under extreme conditions.

Behavior Reproduction

Since the model attempts to integrate the archetypical capability trap model and the basic project model, it should be able to generate behavior of both models. The model is capable of generating the s-shaped curve (as shown in fig 73) for work released over time. This could easily be achieved by turning off all the sensitivity parameters by setting them to zero and changing the value of Fraction of Workforce to Production Effort to from 0.94 to 1. In this case, the capability of the project team declined as there was no effort invested in capability development. However, as the model was made insensitive to capability it did not have any impact on project performance. Such a situation is not realistic.

Fig 73: P-C Trap Model - Work released over time

The output of the revised project model cannot be directly compared with that of capability trap archetypical model. This is because the steady state progress rate in project capability trap model is used to capture output per week as a snapshot once the project has reached the closeout phase, the output in archetypical project model captures the behavior over time of output. To prove that the new project model behaves similarly to the capability trap archetype, the model was simulated five times- under base case conditions, under a work harder condition where the Fraction of Workforce to Production Effort was set to 0.98, a work harder only condition where entire workforce was distributed towards production activities and a work smarter condition where the Fraction of Workforce to Production Effort (FWPE) was set at 0.80, and a work smarter condition where excessive resources were devoted to improvement effort by setting the Fraction of Workforce to Production Effort to 0.20 . The value of Fraction of Workforce to Production Effort was the only difference between these five simulations. The project scope was set to 1000, this change helps us capture the difference in behavior of these five conditions better.

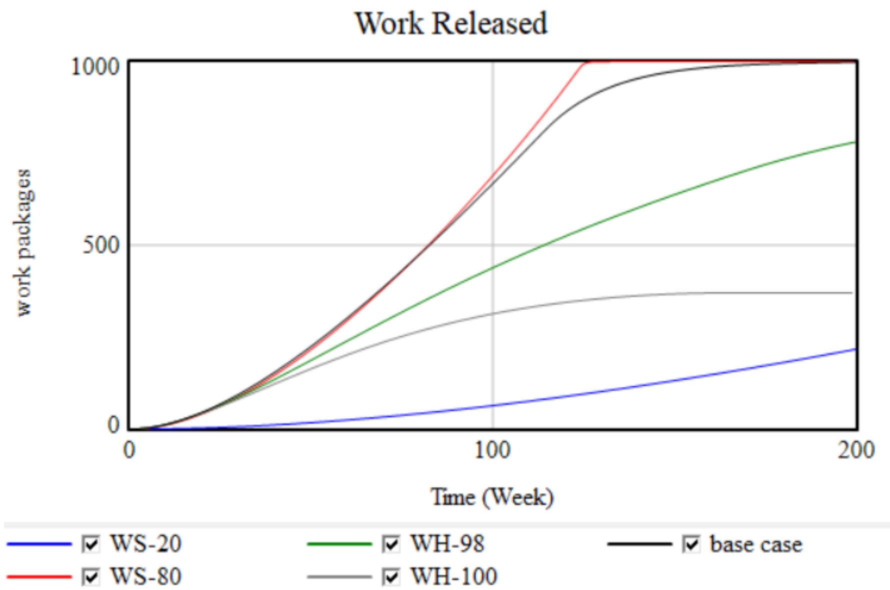


Fig 74: BOTG work released, P-C Trap model

When we examine the behavior over time graphs of these five simulations, we can observe that the work smarter curve with FWPE set to 0.8 completes the work much quicker than base case conditions whereas both work harder condition requires longer to complete the project than base case conditions and have failed to complete the project within stipulated time (Fig 74). However, when the fraction of workforce to production effort was set to 0.2 representing an extreme case of work smarter the system produced the poor performance which was worse than the performance when model was set to work harder only. This occurs because of insufficient workforce put towards production activities. A closer look at the same graph (as seen in Fig 75) reveals that in initial stages work harder conditions were more successful in releasing work quicker than base case conditions and work smarter conditions was releasing less work than base case conditions.

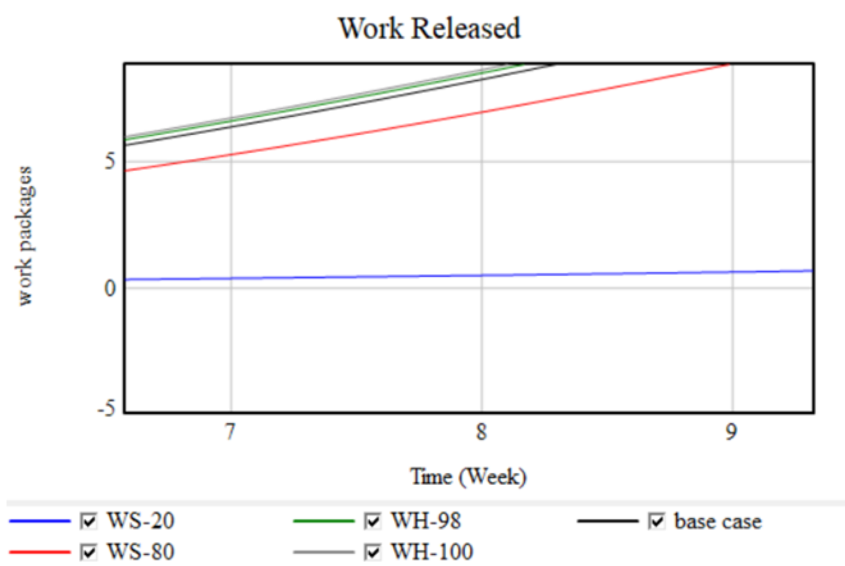


Fig 75: a closer look of BOTG work released, P-C Trap model

Fig 76: Steady State Progress rate, P-C Trap Model

From figure 76, we can observe that working smarter had a significantly higher steady state progress rate when compared to working harder conditions. Figure 77 shows us that the model is calibrated such that the capabilities are constant under base case conditions. Also, figure 77 depicts the capability growth under working smarter conditions and capability erosion under working harder conditions.

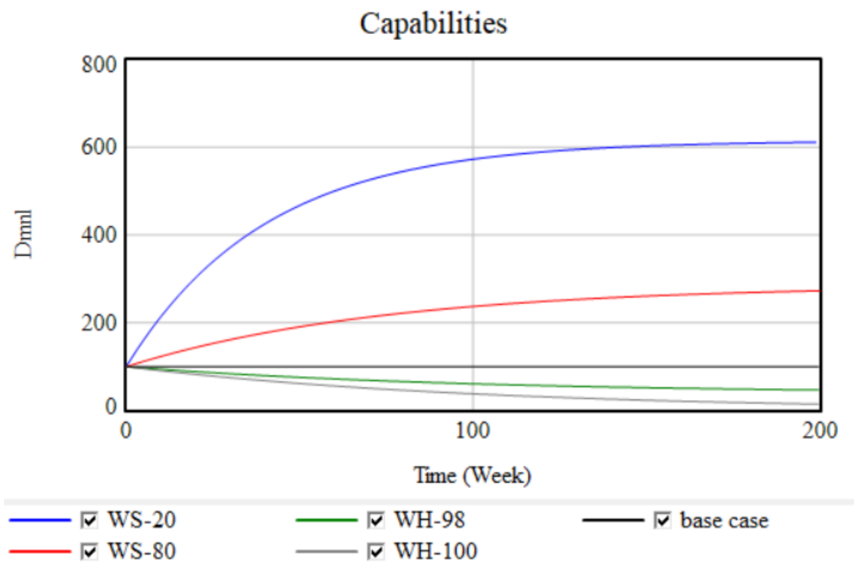


Fig 77: Capabilities, P-C Trap Model

Consider a case where entire workforce is set to production activities, however at around week 100, the project manager realizes that the progress rate is slowing down due to loss of capability. The project manager then allocates about 20 % of the workforce towards capability development. Fig 78 captures the behavior over time of work released. Fig 79 compares the approval rate of this case against the work harder only case. A close observation of Fig 79 reveals a dip in approval rate as the system switches from work harder to work smarter. At this time the work released also slows down as observed in Fig 78. From this graphical evidence, it can be observed that the model produces a worse before better behavior under work smarter conditions and a better before worse behavior under work harder conditions.

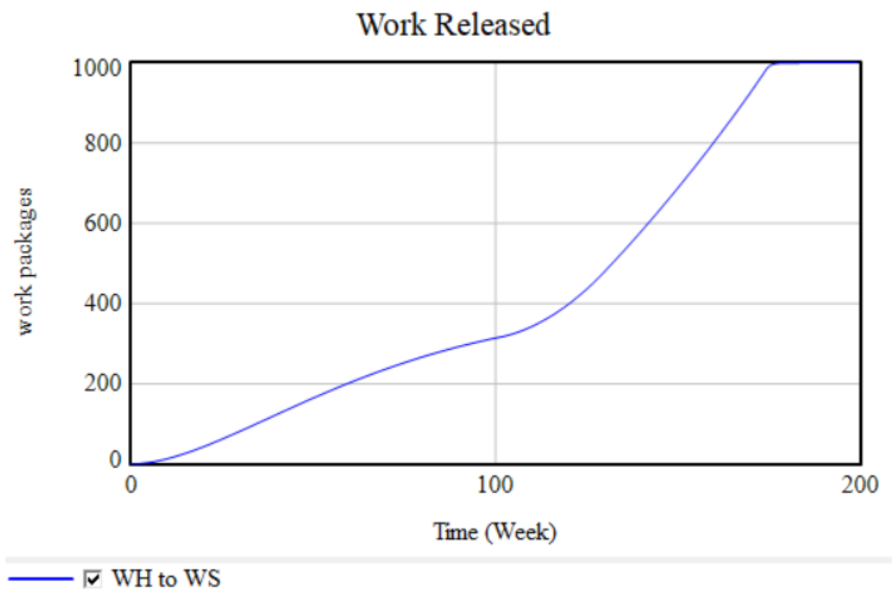


Fig 78: BOTG Work released – work harder to work smarter switch, P-C Trap Model

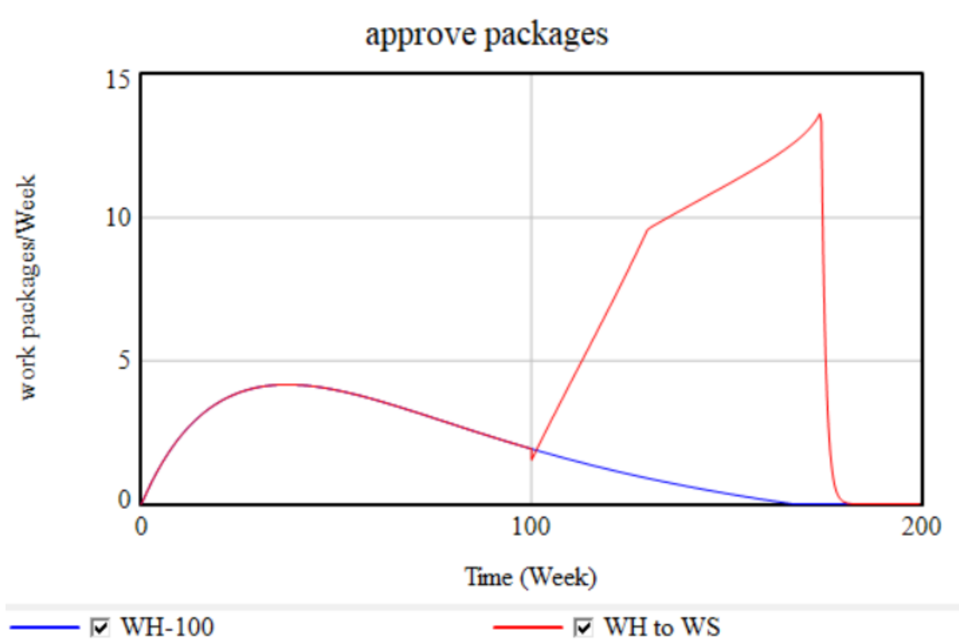


Fig 79: BOTG Approval rate – WH only and WH to WS switch cases, P-C Trap Model

Behavior Anomaly

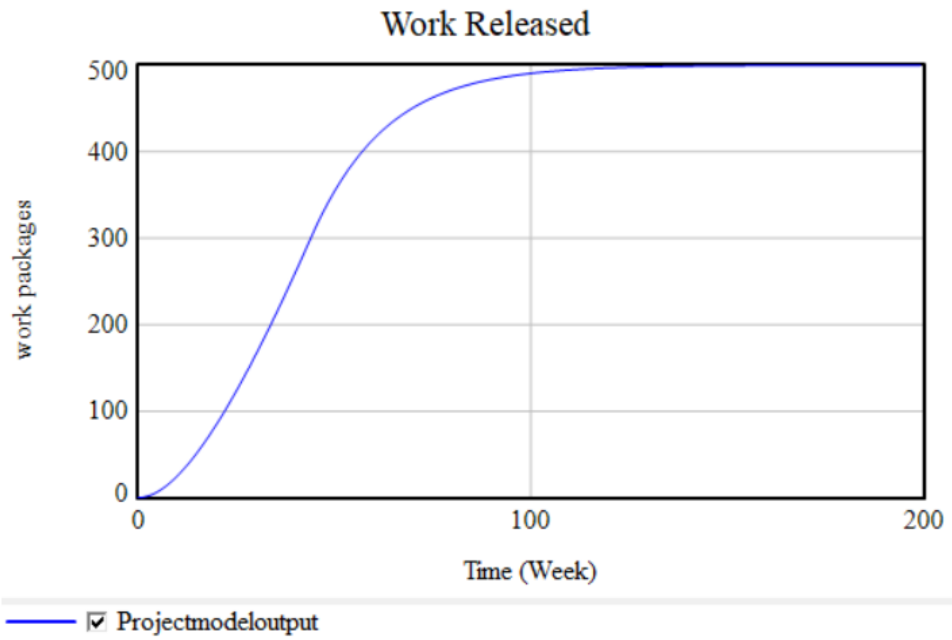


Fig 80: Capability Loop Knockout Test, P-C Trap Model

A loop knockout tests were administered on the P-C trap model. The model proved to be robust and have a consistent behavior even when certain loops were made ineffective. The capability loop was made ineffective by reducing all the sensitivity values to zero and the model performed as expected (Fig 80). Rework loop was made ineffective by setting the fraction of work packages discovered to require rework as zero (Fig 81). The model behaved consistently and was still able to produce the S-shaped curve for work released over time. As expected, the time to complete the project reduces significantly when compared to the base case conditions.

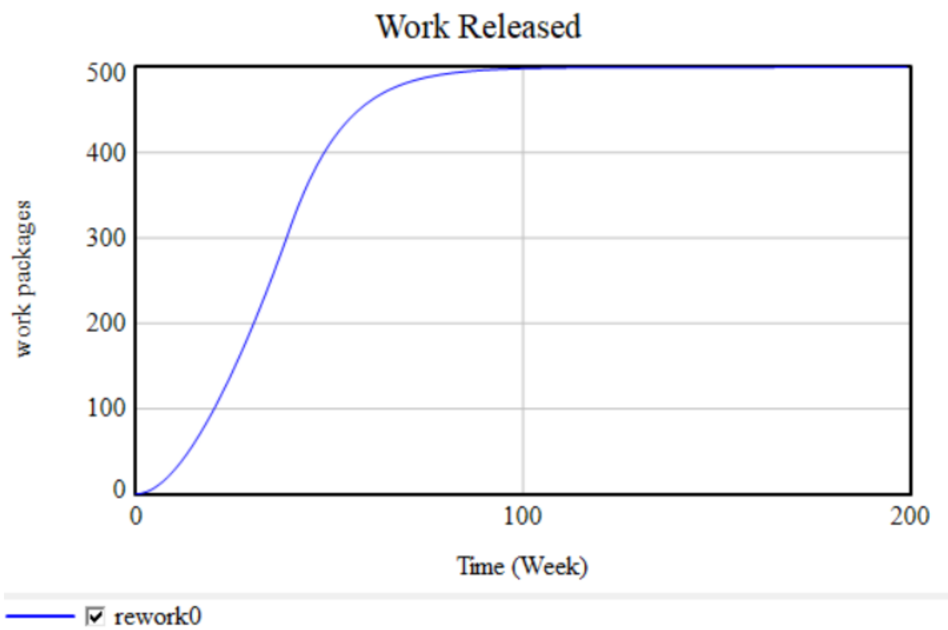


Fig 81: Rework Loop Knockout Test, P-C Trap Model

Integration Error

The results of the integration error test shows us that the model is not very sensitive to time step or numerical integration techniques. The simulation was run for base case parameters. The graph shows the behavior of output over time for time steps equal to 0.015625 weeks, 0.03125 Weeks, 0.0625 Weeks, 0.0125 weeks, 0.25, 0.5 weeks and 1 Week. The difference between these cases are not significant (fig 82), all of them show the same behavior and attain the same equilibrium.

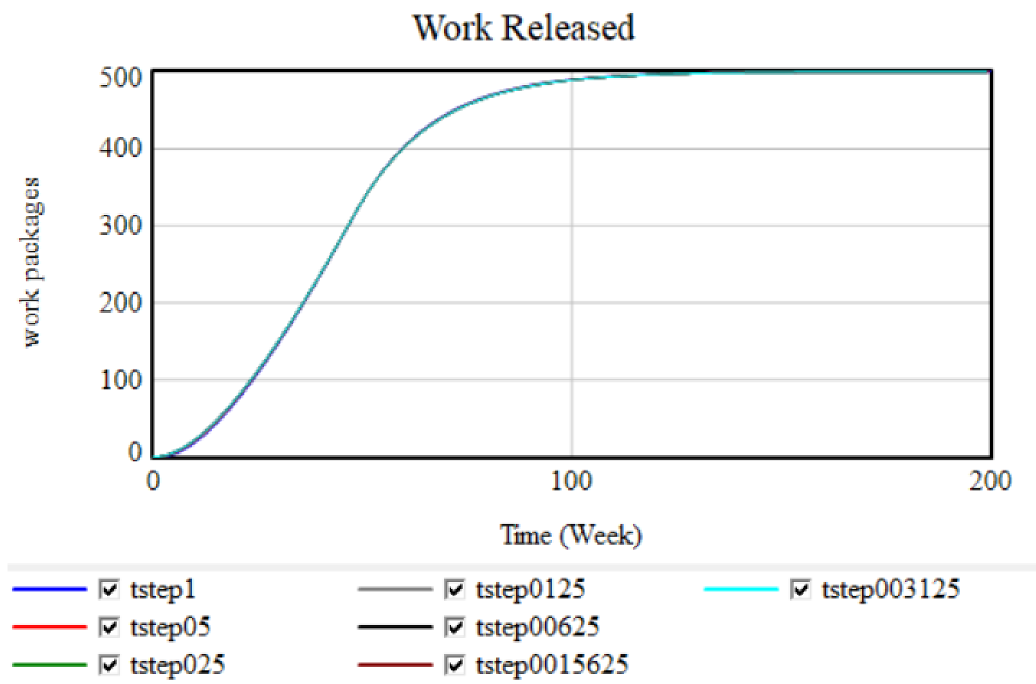


Fig 82: Sensitivity - variation in timestep, P-C Trap Model

Surprise Behavior

The model was simulated under various time steps and for different durations. These tests also included varying all the time constants, scope, error fraction and productivity. However, the model behaved consistently.

Sensitivity Analysis

This model was subjected to univariate sensitivity analysis. Total Project staff, production and capability staff effort rate, productivity of production staff and fraction of workforce to production were found to be high leverage points in this system. The results of this test has been included in the analysis.

Model Use

This model was subjected to univariate sensitivity analysis and used to study the research questions posed in the study titled "Capability traps in construction projects".

APPENDIX D

LIST OF ATTACHMENTS

This work is supported by the following list of attachments included as separate files:

- Model assessment result file of the capability trap model
- Model assessment result file of the project model
- Model assessment result file of the project capability trap model
- The capability trap model
- The project model
- The project capability trap model