A Systems Approach to Mitigation of Project Failure Modes

by

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Abstract

This thesis sets out to develop a systems approach towards the mitigation of project failure modes. The methodology used is the application of the Scope and Solution Neutrality principle to develop a general model for Project Systems using the Object-Process-Method (OPM) for systems modeling. By correlating the elements and attributes that constitute basic project artifacts with process performance enablers, a Systems Approach to Performance Improvements is developed. Systemic factors that affect a project's performance, and its ability to address issues, are identified using the Project System model, and project failure modes as well with their underlying causes are examined. The Systems Approach to Process Improvements is then applied to addressing these issues.

A key insight gained from the modeling is the importance of communication and information flow as a critical function for effective project management and execution. Consequently the impact of optimizing information flow on project execution is demonstrated through systems dynamics modeling.

Thesis Advisor

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Motivation

This thesis was inspired by my professional experiences in the field of Project Management. My motivation to pursue the subject matter was primarily to aid my own understanding of why I repeatedly observed similar, and yet at the same time completely context specific issues on some of the projects that I have worked on; particularly:

- The Big Dig Boston, US Honeywell Technology services Inc.
- Iraq Reconstruction Iraq Perini Management Services Inc.
- Aweer Power Plant Dubai, UAE Schema Management Group LLC

While many of the problems faced on these projects could have been analyzed as case studies, I wanted to avoid taking that direction, simply because there is always an impediment in applying lessons learned from a previous experience into a new context.

Instead, I considered it would be far more valuable to use this collective experience, and a systems analysis approach, to develop process improvement and failure mitigation methodologies that could be applied to any project, regardless of its context.

Acknowledgements

I would first like to thank my thesis advisor, Professor Olivier de Weck, for his support over the last year, his advice in this effort, and foremost, for encouraging me to pursue a thesis that I could be proud of.

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I owe a debt of gratitude to the MIT-MASDAR Initiative for their support in enabling me to pursue this degree, and for providing the opportunity to work with some remarkable people on a remarkable research project.

I would like to thank Dr. Anas Al Faris for his friendship and his great advice, and all my friends amongst the student body and faculty of the System Design and Management program, who made the last couple of years such a memorable experience.

I would like to thank my parents for laying the foundations of everything I have achieved in life, and my children for putting up with their father when he always had work to do.

And lastly, and most importantly, I would like to thank my wife, Nadya, without whose encouragement, I would never even have started this journey, and without whose support I couldn't have seen it through completion.

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1. Introduction

For as long as human beings have been attempting creative endeavors the discipline of Project Management has been practiced. The fact that it still remains a subject of robust scholarly interest is a testament to both its importance and its complexity.

From the outset we can be assured that attempting to delimit the scope of Project Management would be futile. If we take into consideration that every effort at managing a particular project is intrinsically and uniquely tied to the project itself, we would recognize that in a world of seemingly infinite projects, the range of possible approaches to Project Management are also infinite.

Nor would it make sense to arbitrarily decide that there is a particular, 'most critical', aspect of Project Management. In reality the most critical aspect of managing a project is always the one that is most likely to cause failure or loss at any given moment. As a well known axiom states:

> *Everything needs to work in order for the project to succeed, but a single part's failure can cause the entire project to fail.*

This implies that during the course of a project, a multitude of issues at various times could potentially be jeopardizing its chances of success. Unfortunately, without studying a particular project and its context specifically, it is impossible to predict which issues are most likely to afflict it, and to what degree.

Of course this presents a significant challenge from the perspective of the stated goal of this thesis: to identify widely applicable failure mitigation strategies for projects. How does one establish an approach, or define focus in such a multi-faceted discipline? One where there is potentially such a vast range of unknown risks; and such variety in the nature of projects and the contexts in which they are executed?

In a professional environment, where the project of interest is already established, it is far too common to see the “focus on the problems” approach. In this approach Project Management is viewed as a set of independent functions, and failure mitigation effort is focused on those functions which are perceived to be under threat. Ideally the proficient Project Manager would be adept at assessing the potential array of risks to the project, and would apply his or her resources towards them accordingly. However, in a fast paced project where the issues are constantly in flux, this approach can quickly end up being highly reactive and issue specific (a.k.a. fire fighting).

Academically, a common approach to addressing project diversity is to focus either by industry (i.e. Software, Construction, Aerospace etc.), or by project issues (i.e. Scheduling, Resource management, Cost management, Risk Management etc.).

In all the examples described above the basic approach is one of specialization. From a learning perspective they *can* all be very useful; that is as long as you can find references that match closely to the context and issues that you perceive in your own project of interest.

An ancient saying derived from **Sun Tzu's: Art of War**, however, hints at another way of approaching the problem:

> *"Know the enemy and know yourself; in a hundred battles you will never be in peril. When you are ignorant of the enemy, but know yourself, your chances of winning or losing are equal. If ignorant both of your enemy and yourself, you are certain in every battle to be in peril."*

Viewed in the context of Project Systems the *enemies* are the multitude of context specific issues that might confront a project. Traditionally, it is these enemies that are the primary focus of the Project Manager - and for good reason. But from the generalist perspective of this thesis, these issues are indefinite, and their impact unquantifiable. Taking cue from the axiom, we focus instead on understanding the Project System itself and seek strategies to strengthen the system as a means to prepare against the potential occurrence of these issues. In other words we seek a systemic approach to improving the Project System in such a way that the chances of external issues becoming a problem are mitigated.

Specifically there are three key objectives that we set out to achieve:

- **Identify systemic factors that influence overall Project performance**.
  Improving overall performance should allow failure modes to be addressed more efficiently should they manifest themselves.

- **Identify systemic factors that influence the ability of the Project System to identify problems when they occur.** Rapid failure or issue discovery would improve the project's ability to mitigate its impact.
- **Develop a systems approach towards process improvements that can be applied to any process within the project.** Applying such an approach from the outset, across the board on all processes could fundamentally strengthen the system and mitigate the chances of potential problems turning into actual failures.

1.1. Approach and Methodology

This thesis deliberately moves away from an issue specific approach and addresses the subject in a holistic and solution neutral manner instead. The means for doing so is the utilization of **Object Process Methodology (OPM)** to model the architecture of a generalized project management system. Thereby allowing the identification of systemic issues within the problem space without becoming influenced by context specific issues that can vary dramatically based on the scale, complexity and the industry within which a project is being executed. If successful in identifying systemic factors that influence project performance, these theoretical conclusions can then be tested using Systems Dynamics modeling.

1.2. Thesis Objectives

To: Investigate methodologies for mitigating project failure modes

By: 1) Understanding the complexity, interactions and dynamics of project systems

2) Identifying systemic factors that may influence project's overall performance and its ability to address failure modes

3) Developing a systems approach for process improvements

4) Understanding the nature and manifestations of project failure modes

5) Demonstrating how a systems approach to process improvements can mitigate project failure modes

6) Empirically demonstrating the impact systemic factors can have on project performance

Using: 1) Systems Architecture for systems analysis

2) Systems Dynamics for experimental evaluation

2. Project System Architecture

2.1. Object-Process-Methodology

2.1.1. Brief Formal Introduction to OPM [1]

Object Process Methodology (OPM) is a holistic approach for conceptual modeling of complex systems. The OPM model integrates the functional, structural, and behavioral aspects of a system in a single, unified view, expressed bi-modally in equivalent graphics and text with built-in refinement-abstraction mechanism.

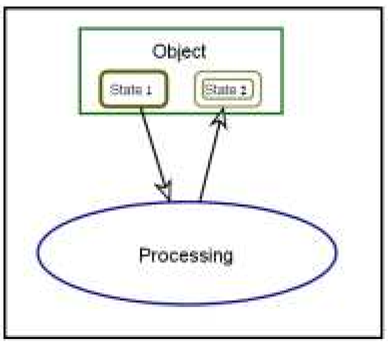


Figure 1: An Object-Process Diagram (OPD) showing the three OPM entities: Object, Process, and State, and the input/output procedural link pair, which expresses that Processing changes Object from State 1 to State 2.

Figure 1: OPM Example

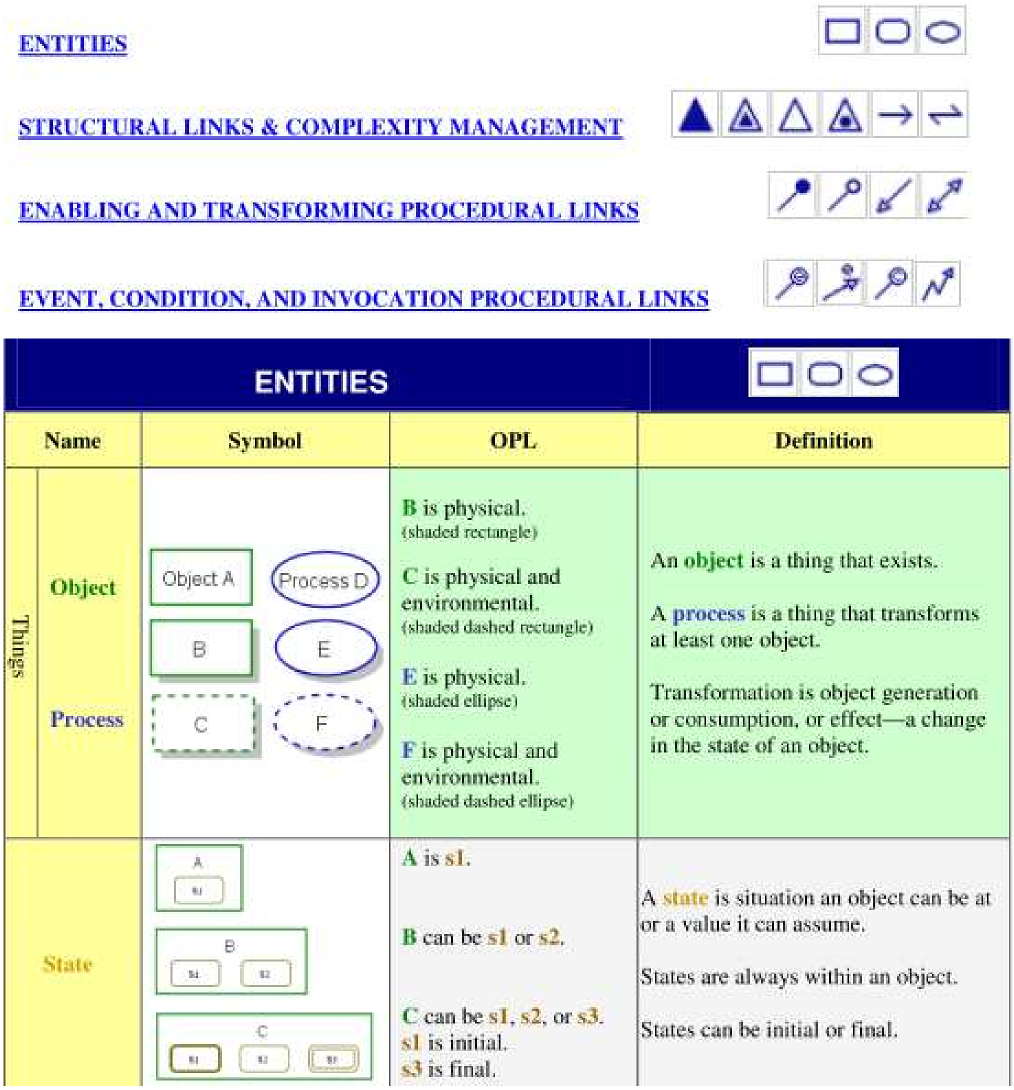
Two semantically equivalent modalities, one graphic and the other textual, jointly express the same OPM model. A set of inter-related hierarchically organized Object-Process Diagrams (OPDs), showing portions of the system at various levels of detail, constitute the graphical, visual OPM formalism. The OPM ontology comprises entities and links. Each OPM element (entity or link) is denoted in an OPD by a symbol, and the OPD syntax specifies correct and consistent ways by which entities can be connected via structural and procedural links, such that each legal entity-link-entity combination bears specific, unambiguous semantics (see Figure 1 for example). There are three different types of entities: objects, processes (collectively referred to as "things"),

[1] Excerpt from OPCAT v3.0 - Getting Started Guide. OPCAT Inc.(2007)

and states. These entities are shown in Figure 1. Objects are the (physical or informatical) things in the system that exist, and if they are stateful (i.e., have states), then at any point in time they are at some state or in transition between states. Processes are the things in the system that transform objects: they generate and consume objects, or affect stateful objects by changing their state.

Links can be structural or procedural. Structural links express static, time-independent relations between pairs of entities. The four fundamental structural relations are aggregation-participation, generalization-specialization, exhibition-characterization, and classification-instantiation. General tagged structural links provide for creating additional "user-defined" links with specified semantics. Procedural links connect processes with objects or object states to describe the behavior of a system. System behavior is manifested in three ways: (1) a processes can transform (generate, consume, or change the state of) one or more objects; (2) an object can enable one or more processes without being transformed by them, in which case it acts as an agent (if it is human) or an instrument; and (3) an object can trigger an event that invokes a process if some conditions are met. Accordingly, a procedural link can be a transformation link, an enabling link, or an event link. A transformation link expresses object transformation, i.e., object consumption, generation, or state change. Figure 1 shows a pair of transformation links, the input/output link. It expresses in OPL that Processing changes Object from State 1 to State 2. An enabling (agent or instrument) link expresses the need for a (possibly state-specified) object to be present in order for the enabled process to occur. The enabled process does not transform the enabling object. An event link connects a triggering entity (object, process, or state) with a process that it invokes.

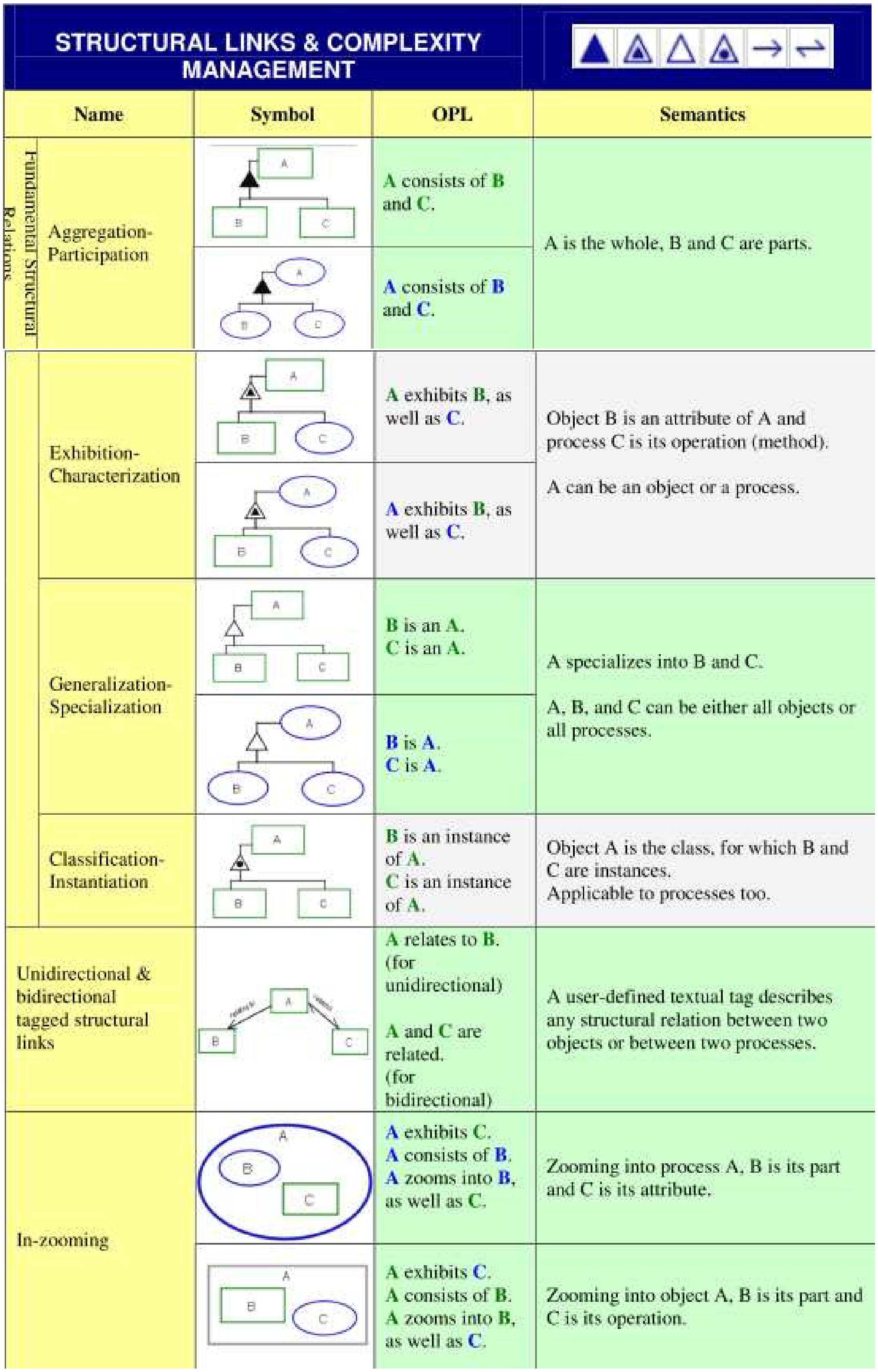
2.1.2. Elements of the Object Process Methodology Language[2]



Name	Symbol	OPL	Definition
Things: Object, Process	Object A, Process D, B, E, C, F	**B** is physical. (shaded rectangle) **C** is physical and environmental. (shaded dashed rectangle) **E** is physical. (shaded ellipse) **F** is physical and environmental. (shaded dashed ellipse)	An **object** is a thing that exists. A **process** is a thing that transforms at least one object. Transformation is object generation or consumption, or effect—a change in the state of an object.
State	A, B, C	**A** is **s1**. **B** can be **s1** or **s2**. **C** can be **s1**, **s2**, or **s3**. **s1** is initial. **s3** is final.	A **state** is situation an object can be at or a value it can assume. States are always within an object. States can be initial or final.

Figure 2: OPM Entities

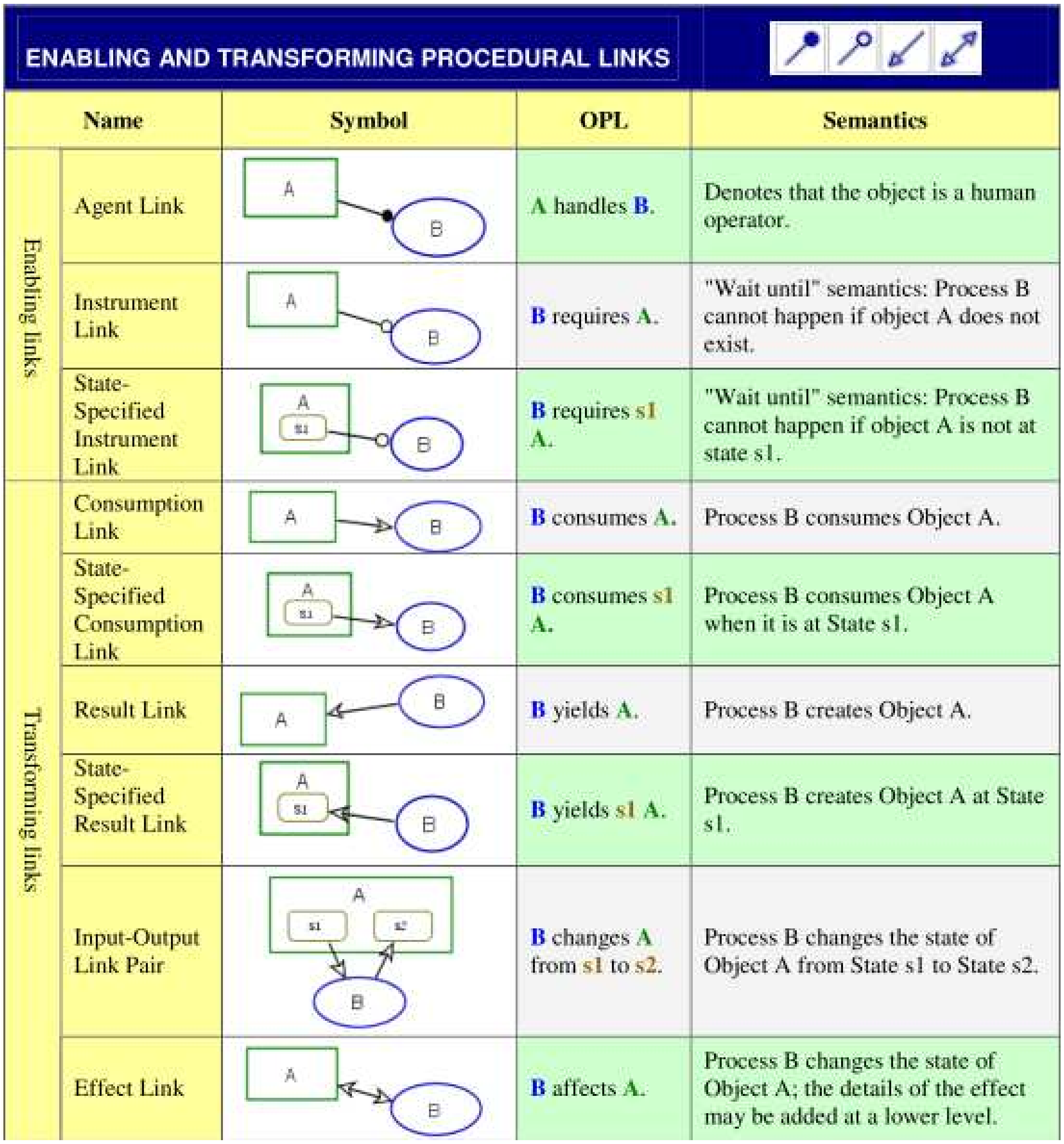
[2] Excerpt from OPCAT v3.0 - Getting Started Guide. OPCAT Inc.(2007)



STRUCTURAL LINKS & COMPLEXITY MANAGEMENT

	Name	Symbol	OPL	Semantics
Fundamental Structural Relations	Aggregation-Participation		A consists of B and C.	A is the whole, B and C are parts.
			A consists of B and C.	
	Exhibition-Characterization		A exhibits B, as well as C.	Object B is an attribute of A and process C is its operation (method). A can be an object or a process.
			A exhibits B, as well as C.	
	Generalization-Specialization		B is an A. C is an A.	A specializes into B and C. A, B, and C can be either all objects or all processes.
			B is A. C is A.	
	Classification-Instantiation		B is an instance of A. C is an instance of A.	Object A is the class, for which B and C are instances. Applicable to processes too.
Unidirectional & bidirectional tagged structural links			A relates to B. (for unidirectional) A and C are related. (for bidirectional)	A user-defined textual tag describes any structural relation between two objects or between two processes.
In-zooming			A exhibits C. A consists of B. A zooms into B, as well as C.	Zooming into process A, B is its part and C is its attribute.
			A exhibits C. A consists of B. A zooms into B, as well as C.	Zooming into object A, B is its part and C is its operation.

Figure 3: OPM Structural Links



ENABLING AND TRANSFORMING PROCEDURAL LINKS

	Name	Symbol	OPL	Semantics
Enabling links	Agent Link		A handles B.	Denotes that the object is a human operator.
	Instrument Link		B requires A.	"Wait until" semantics: Process B cannot happen if object A does not exist.
	State-Specified Instrument Link		B requires s1 A.	"Wait until" semantics: Process B cannot happen if object A is not at state s1.
Transforming links	Consumption Link		B consumes A.	Process B consumes Object A.
	State-Specified Consumption Link		B consumes s1 A.	Process B consumes Object A when it is at State s1.
	Result Link		B yields A.	Process B creates Object A.
	State-Specified Result Link		B yields s1 A.	Process B creates Object A at State s1.
	Input-Output Link Pair		B changes A from s1 to s2.	Process B changes the state of Object A from State s1 to State s2.
	Effect Link		B affects A.	Process B changes the state of Object A; the details of the effect may be added at a lower level.

Figure 4: OPM Enabling and Transforming Links

EVENT, CONDITION, AND INVOCATION PROCEDURAL LINKS

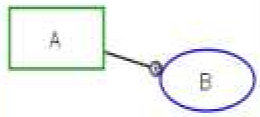
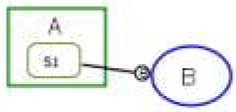
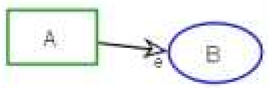
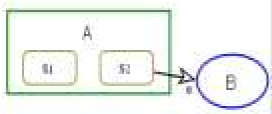
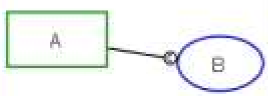
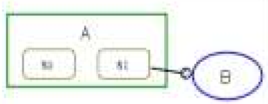
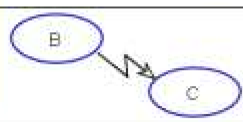
Name	Symbol	OPL	Semantics
Instrument Event Link		**A** triggers **B**. **B** triggers **A**.	Existence or generation of object A will attempt to trigger process B once. Execution will proceed if the triggering failed.
State-Specified Instrument Event Link		A triggers **B**. when it enters **s1**. **B** requires **s1** **A**.	Entering state s1 will attempt to trigger the process once. Execution will proceed if the triggering failed.
Consumption Event Link		**A** triggers **B**. **B** consumes **A**.	Existence or generation of object A will attempt to trigger process B once. If B is triggered, it will consume A. Execution will proceed if the triggering failed.
State-Specified Consumption Event Link		**A** triggers **B** when it enters **s2**. **B** consumes **s2** **A**.	Entering state s2 will attempt to trigger the process once. If B is triggered, it will consume A. Execution will proceed if the triggering failed.
Condition Link		**B** occurs if **A** exists.	Existence of object A is a condition to the execution of B. If object A does not exist, then process B is skipped and regular system flow continues.
State-Specified Condition Link		**B** occurs if **A** is **s1**.	Existence of object A at state s2 is a condition to the execution of B. If object A does not exist, then process B is skipped and regular system flow continues.
Invocation Link		**B** invokes **C**.	Execution will proceed if the triggering failed (due to failure to fulfill one or more of the conditions in the precondition set).

Figure 5: OPM Event, Condition and Invocation Procedural Link

2.2. Assumptions and Approach

The primary goal of this modeling effort was to be able to understand the basic features of Project Systems. However, the foremost challenge towards pursuing such a goal is the reality that there is no such thing as a standard project or a standardized approach to project management.

An approach that was actually attempted initially, but ultimately rejected was to begin by modeling a case study project. However, what became quickly evident was that the model became a reflection of that specific project's considerations rather than demonstrating the systemic project related issues that were being sought.

The stated goal of trying to identify means for mitigating project failures in general, dictated that the model needed to establish a common denominator for all project systems. The following principles were therefore applied in order to achieve this:

- Focus primarily on defining those project related processes that are always or almost always present
- Allow these processes to govern which objects should be included as essential inputs, outputs, instruments and agents.
- Expand the model to the extent that scope neutrality and solution neutrality can be maintained

2.3. Project System Model

The resulting model and the concepts applied in developing its structure and elements are as follows:

2.3.1. Project

A **Project** is the intent to satisfactorily fulfill a **Need** through the development of a **Product**. It is deliberately referred to as being the intent so as to be inclusive of all projects, regardless of whether they are successful in meeting their **Product** objectives or not.

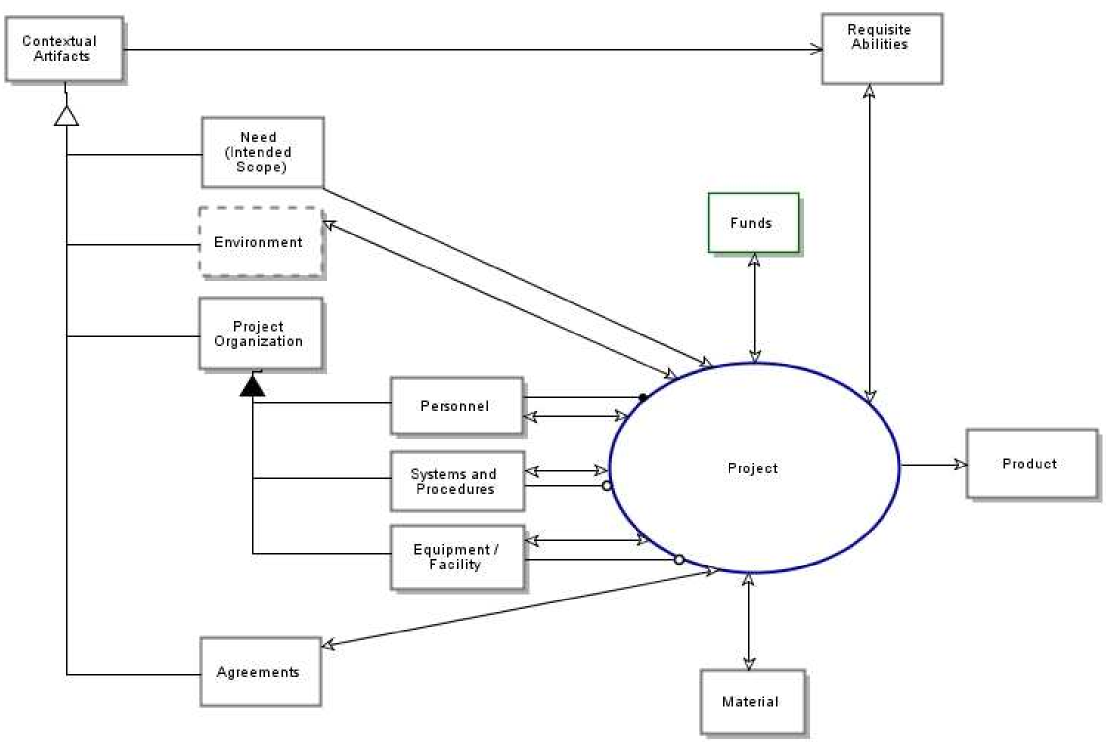


Figure 6: Project System – Level 1

The model represents the **Project** as a process which generates a **Product**. In order to do so it utilizes **Funds** and **Material**. Both of these elements are connected using the *affect* link to reflect that the **Project** must generate them, manage them and utilize them.

Additionally the **Project** uses **Personnel** as *agents*, **Systems and Procedures** as *instruments* and **Equipment/Facility** as *instruments* as well. All three of these are also connected using the *affect* link to indicate that in addition to being *instruments* or *agents,* and being generated by the **Project,** they can have secondary impacts on the **Project** as well.

2.3.2. Project Organization

Collectively the three elements of **Personnel**, **Systems and Procedures** and **Equipment/Facility** constitute the **Project Organization**. Staying consistent with the solution neutral principle, the structure of the Organization has not been defined. In reality it could be any combination of owner, contractors, or agents, not to mention departmental divisions that might exist in any of them. However, the only element that would always have to be present is the owner. To make note of the critical impact that the **Organizational Structure** can have it is included as an attribute in the detailed **Project Organization** model

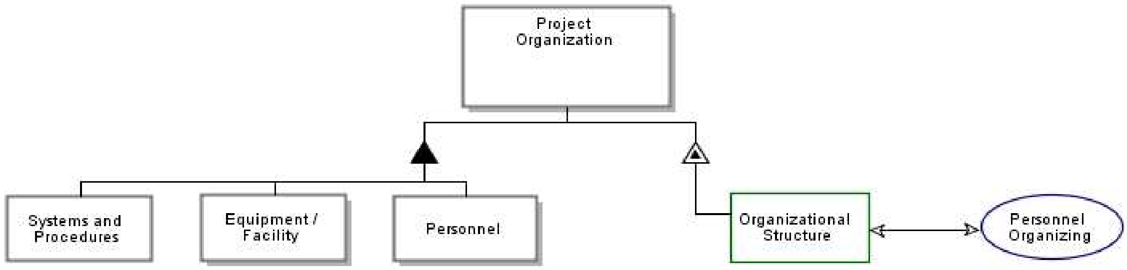


Figure 7: Project Organization

2.3.3. Need (Intended Scope)

This is the indispensible input required for the **Project** function to initiate. It is also what we would consider to be an entirely project/context specific element. Nevertheless, regardless of the particular need that requires fulfillment, from a systems perspective we are able to define it in terms of the types of information that we expect it to consist of, as well as a set of attributes that it is expected to exhibit.

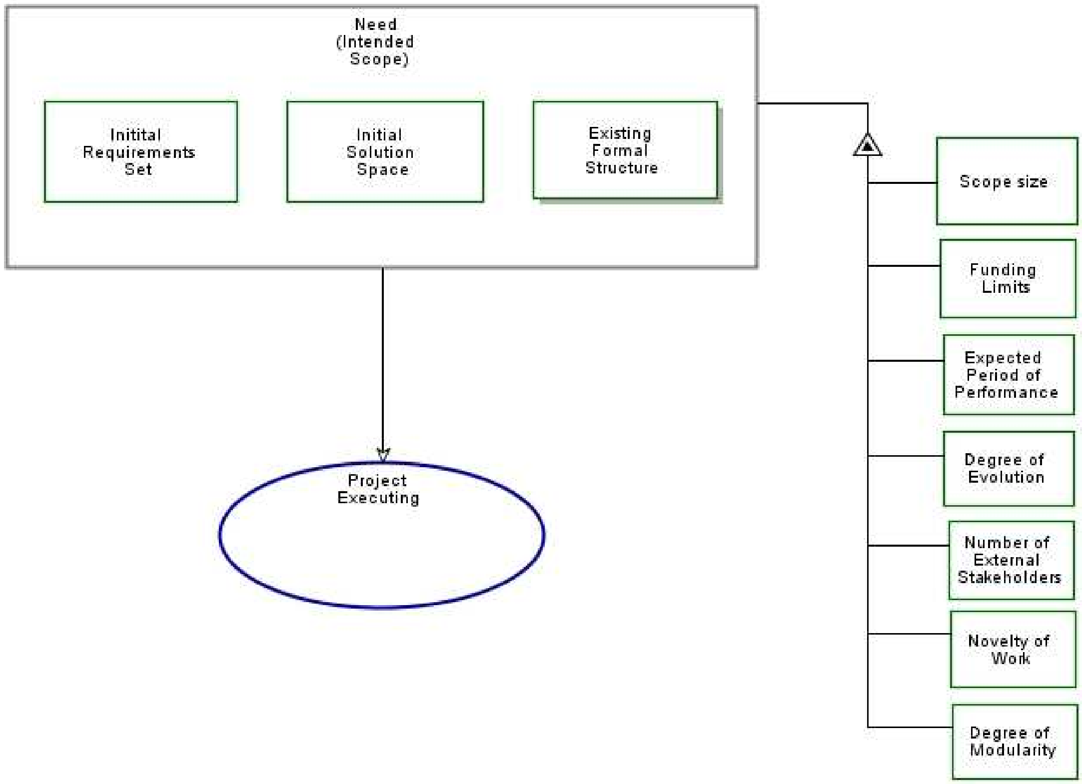


Figure 8: Need (Intended Scope)

The main components are the **Initial Requirements Set**, the **Initial Solution Space**, and the **Existing Formal Structure**

- A **Requirements Set** is the collection of information that describes the project objectives and the relevant factors that the **Product** must take into consideration in order to be considered successful.
- A **Solution Space** is a collection of information that reflects the understanding of the nature of the project outcome (i.e. the **Product**), and how it is expected to be actualized.

- **Formal Structure** represents portions of the final **Product** that are already in existence at the time of review

It is important to note that in this model the **Need** is represented as a *static* representation of the *initial* understanding of these elements:

- **Initial Requirements Set –** original project objectives
- **Initial Solution Space –** initial solution expectations
- **Existing Formal Structure -** what is already there to work with

This distinction is made to clarify that while the **Requirement Set**, **Solution Space** and **Formal Structure** *are* expected to evolve over the course of the Project, the *dynamic* natures of these elements are captured elsewhere in the model.

The model also defines a set of *attributes* for the **Need**. This list is not meant to be exhaustive, however, it is a list of factors that can have considerable impact on the **Project System** as a whole:

- Scope Size
- Funding Limit
- Expected Period of Performance
- Degree of Evolution
- Number of External Stakeholders
- Novelty of Work
- Degree of Modularity

2.3.4. Environment

The **Environment** is defined as a combination of physical, regulatory and economic conditions that encompass the **Project System.** While there are potentially an infinite number of environmental considerations that may be relevant to a project, the model focuses on generalized forms of only those factors that can be expected to have a systemic impact on the **Project System**

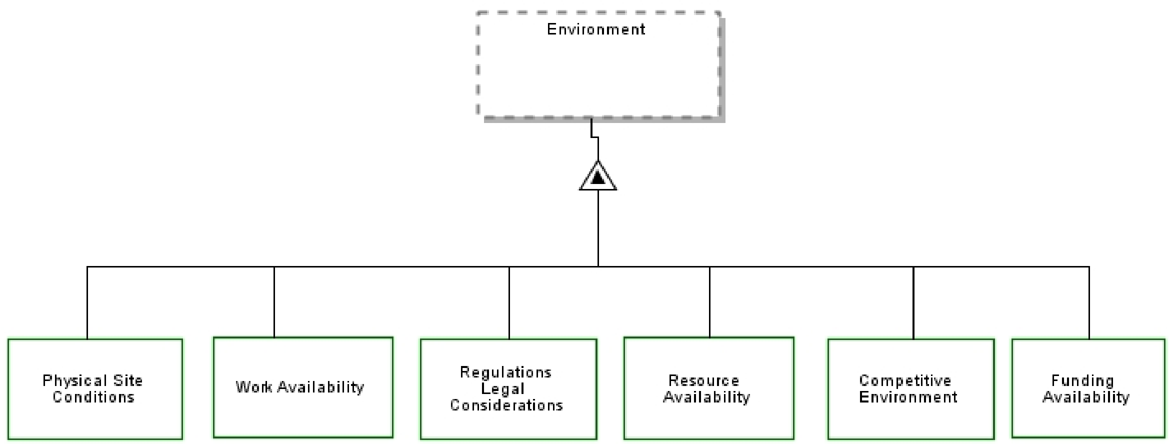


Figure 9: Environment

2.3.5. Agreements

With the exception of an individual executing a personal project on his own, all projects will require some of agreement amongst its participants. Regardless of whether these agreements are formal or informal, or who they are struck between, they can be expected to have a profound impact on the **Project System** as a whole.

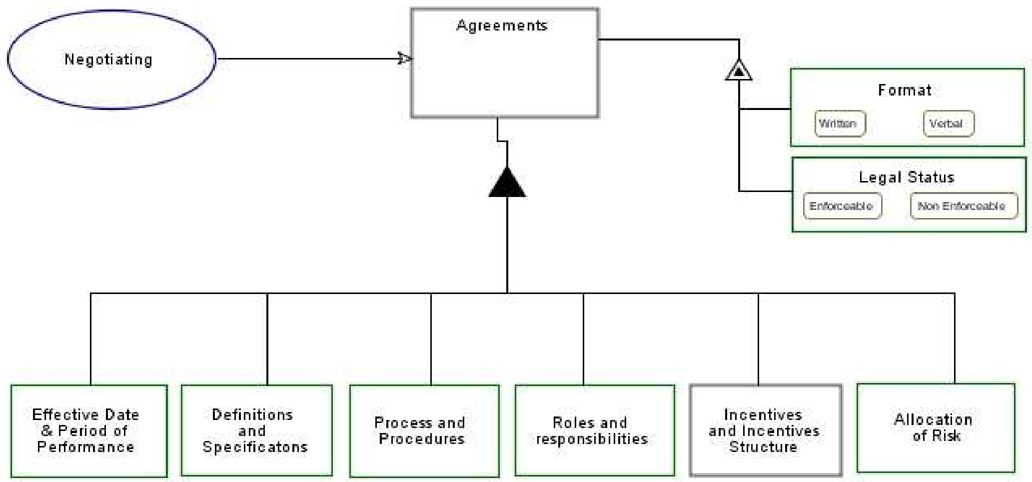


Figure 10: Agreements

Once again the elements that have been included in the model are generalized and limited to the ones that are expected to have systemic effects. They are:

- Effective date and Period of Performance
- Roles and Responsibilities
- Incentives and Incentives Structure (also meant to include punitive measures)
- Processes and Procedures
- Allocation of Risk
- Definitions and Specifications

Attributes of **Agreements** that have been included are:

- Format
    - Verbal
    - Written
- Legal status
    - Enforceable
    - Non-enforceable

In most professional settings **Agreements** will take the form of written and legally enforceable documents; also known as *Contracts*.

2.3.6. Contextual Artifacts

The four elements discussed above

- **Need (Intended Scope)**
- **Environment**
- **Project Organization**
- **Agreement(s)/Contract(s)**

are collectively classified as **Contextual Artifacts.** With the exception of the consumables i.e. **Funds** and **Materials**, and any components that constitute the **Product**, these elements comprise of all the physical and informational objects in the **Project System**. The **Contextual Artifacts** are essential formal elements of the **Project System**; their influence is multi-modal and systemic, and defines the fundamental ability of a **Project System** to operate.

2.3.7. Requisite Abilities of the Project System

For the processes of a **Project System** to be executed there are certain basic abilities that must exist to enable them. The model designates them as **Requisite Abilities** and they are as follows:

- Capability / Capacity to Work
- Ability to Incentivize Work
- Ability to Communicate
- Ability to Monitor Status
- Ability to Make Decisions

Every process in the **Project System** will not require all of these abilities to function. In fact the only one that is always required is **Capability/Capacity to Work**. Nevertheless they constitute a fundamental set of attributes that the Project System as a whole must posses in order to operate.

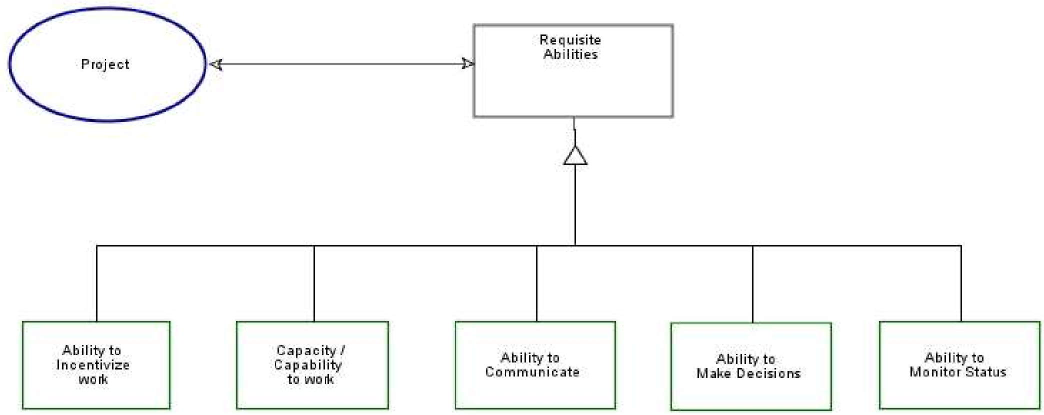


Figure 11: Requisite Abilities

Whether or not the **Requisite Abilities** are present, or present in sufficient strength, depends upon the **Contextual Artifacts**. However, to understand this influence it will be necessary to study each **Contextual Artifact** at the component level. Each component element or attribute of a **Contextual Artifact** has the potential to affect some or all of the **Requisite Abilities**. The **Requisite Abilities** in turn influence the performance of the various **Project System** functions and ultimately, the performance of these functions will be reflected in the **Product**.

2.3.8. Basic Project Processes

If we zoom into the **Project** function we see that it can be divided into two key components:

- Project Executing

- Project Managing

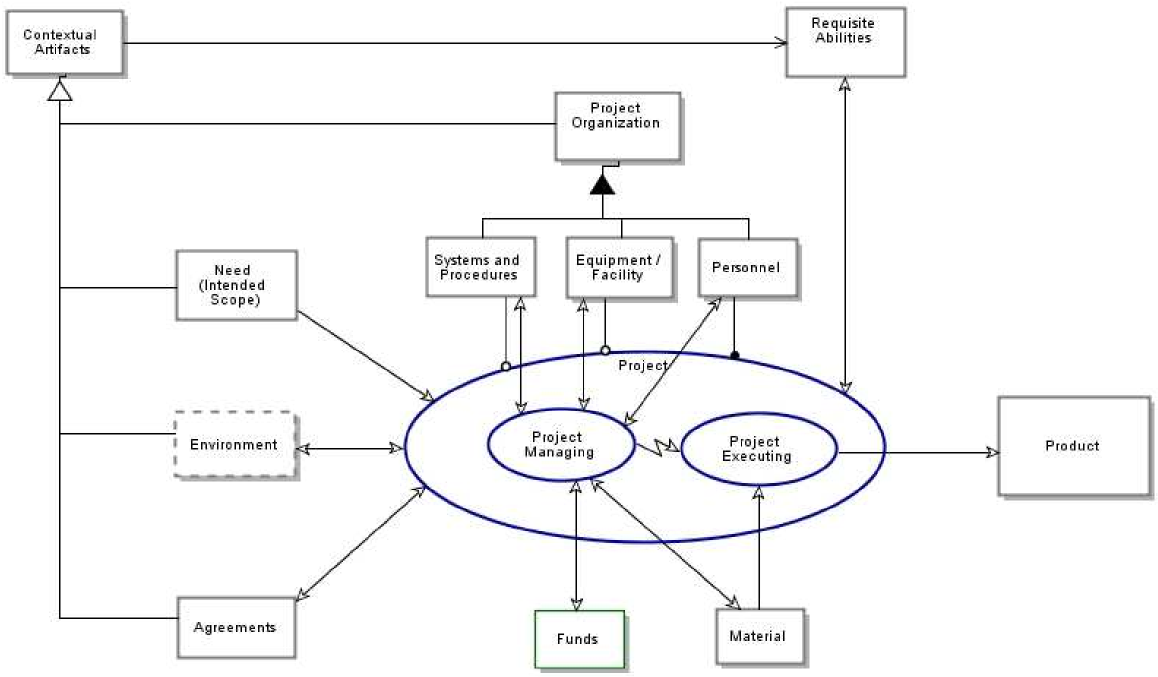


Figure 12: Project System - Level 2

At this level we can also observe that it is the **Project Managing** function that makes the provisions for the **Funds**, **Material**, **Personnel**, **Systems and Procedures** and **Equipment/Facilities** that are utilized by the Project as a whole.

2.3.9. Project Managing

This is a function that plays the part of ensuring the *ability* to conduct execution within the established constraints. There are two key facets to achieving this:

- **Enabling**
    - Fulfilling resource requirements (**Material**, **Equipment**, **Personnel**)
    - Developing the **Systems and Procedures** required to enable the various **Project** functions
    - Planning and enforcing the execution strategy
- **Assessing**
    - Monitoring **Resource Status**, **Execution Status**, and **Cost Information**
    - Assessing status against the plan and specifications
    - Forecasting conditions and identifying required strategy changes

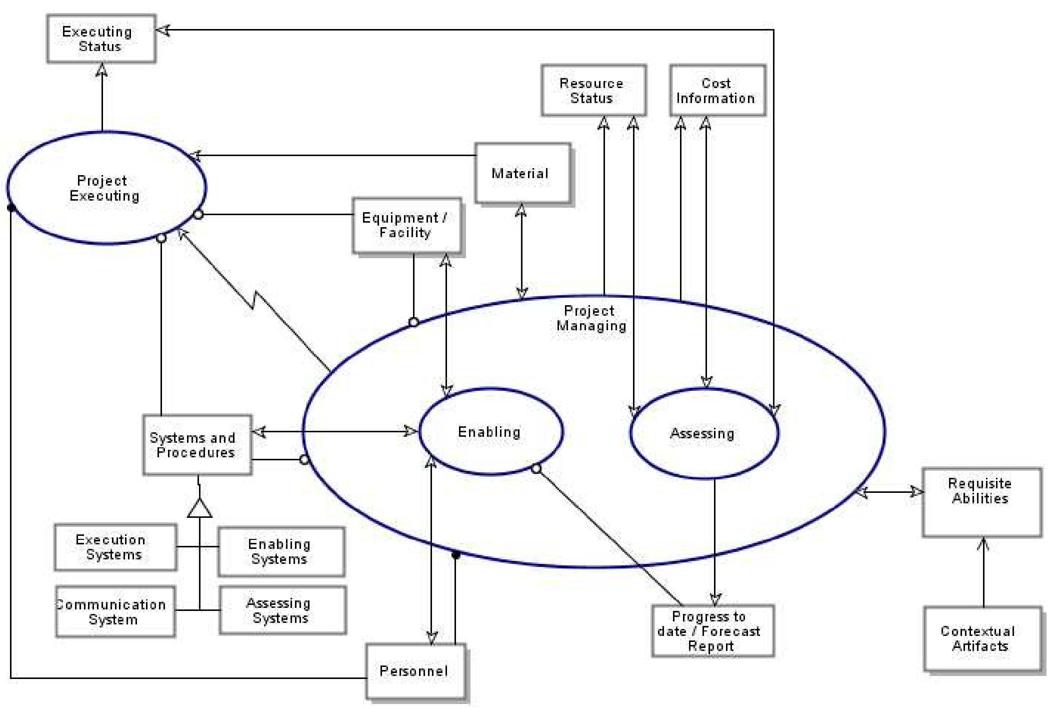


Figure 13: Project Managing

Enabling is a prerequisite for **Executing** to occur while **Assessing** is an on-going oversight function that measures and evaluates both the **Execution** and the **Enabling** processes. The conclusions of this evaluation must flow back into the **Enabling** process if it is to be improved or realigned. This is depicted in the form of **Progress to Date/Forecast Report** acting as an instrument for the **Enabling** process.

At this level we note that **Enabling** generates the **Systems and Procedures** which support not only the **Enabling** function, but the **Executing** and **Assessing** functions as well.

2.3.9.1. Enabling

Zooming into the **Enabling** function allows us to observe how the various outputs are delivered. The OPL Generator allows us to derive the following natural language description of the **Enabling** process from the model:

- Systems / Process Development yields Systems and Procedures
- Financing requires Finance System
- Financing yields Funds
- Negotiating requires Project Delivery Strategy and Scope Allocation and Organization Strategy

- Negotiating yields Agreements
- Personnel Organizing requires Scope Allocation and Organization Strategy
- Personnel Organizing affects Personnel and Organizational Structure
- Hiring requires Personnel Management System
- Hiring yields Personnel
- Equipment / Facility Resourcing requires Equipment/ Facility Resourcing System
- Equipment / Facility Resourcing yields Equipment / Facility
- Material Acquisition and Logistics requires Material Management System
- Material Acquisition and Logistics yields Material
- Scheduling and Resource Utilization requires Scheduling System
- Scheduling and Resource Utilization affects Equipment / Facility, Material, and Personnel
- Scheduling and Resource Utilization yields Schedule
- Estimating requires Estimating System
- Estimating affects Solution Space
- Estimating yields Estimate.

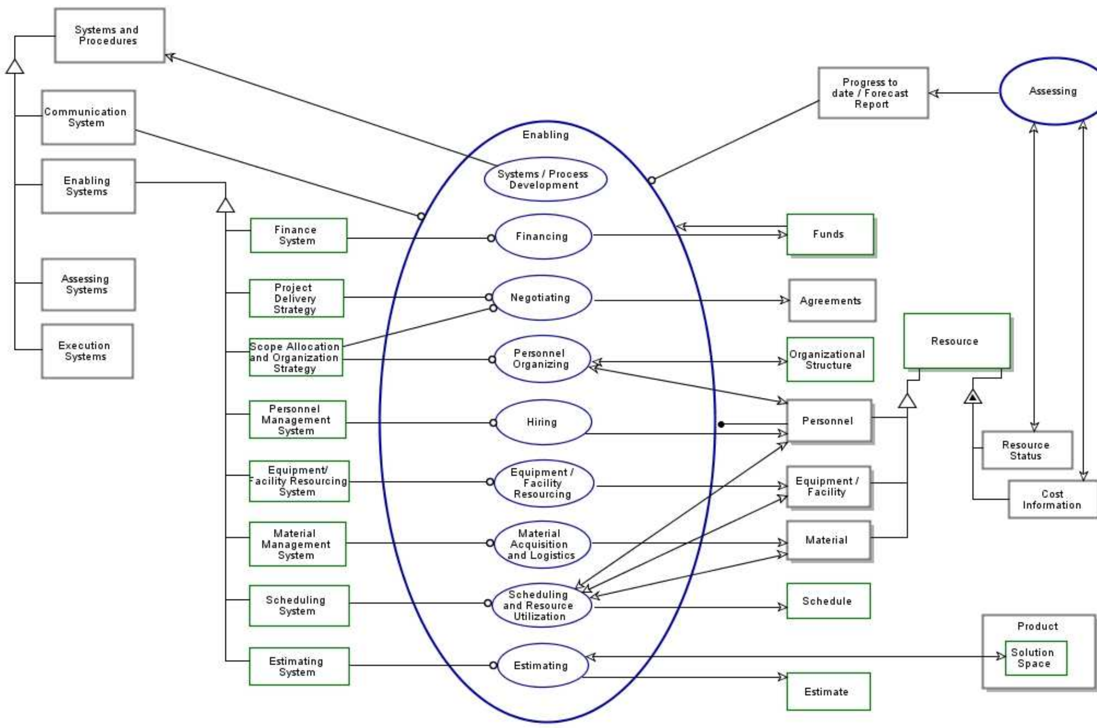


Figure 14: Enabling

2.3.9.1.1. Systems / Process Development

Of all the functions within **Enabling,** the **Systems / Process Development** function is particularly critical. It is the function that develops the set of procedures, protocols and methodologies that are utilized by *each* of the various other functions in the **Project System**. This set of procedures can consist of:

- Functional Procedure – the methodology for executing the primary function (or purpose) of the process

- Participant/Instrument Involvement – which is a listing of participants and instruments (equipment or facilities), that should be involved in the process
- Delegation of work – which allocates the scope of work related with the process amongst the involved participants.
- Information Sharing Protocols – which govern the flow and means of sharing information amongst participants
- Decision Making Protocols – which can include approval methodologies as well as dispute resolution mechanisms
- Authority Delegation – which appoints approval or decision making authorities to specific participants

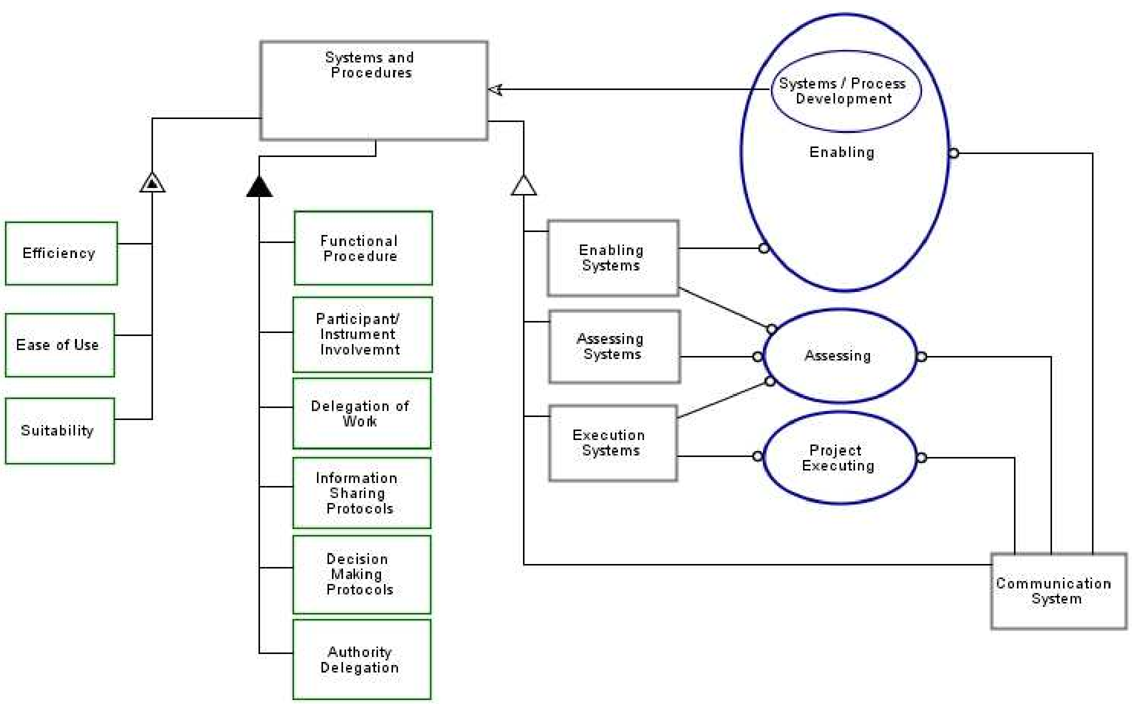


Figure 15: Systems and Procedures

In the vast majority of the cases a set of such procedures will constitute a system dedicated to the enabling of a particular process, i.e. will have a one-to-one *instrument* link with a particular project function. As such these systems are referred to as **Instrument Systems.**

This implies that each **Instrument System** is developed or evolves with the specific purpose of enabling its associated function. On an actual project the performance levels required for each of these functions would depend on the specific needs of that project, and ideally its associated **Instrument System** would be capable of enabling such performance. The systems that exist within the groupings of **Enabling Systems** and **Executing Systems** will for the most part consist of such **Instrument Systems**.

It should be also be noted that within each **Instrument System** set we have the element of **Information Sharing Protocols** which relates to the monitoring and communicating capabilities of that particular process. This also emphasizes that an aspect of communication and monitoring has to be embedded within each process.

However, at the project wide level there also needs to be the means for collecting and managing all of this information coming from and going to the various processes. The **Communication System** represents the project wide methodology which enables this. Where the information in question is specifically related to monitoring of status, the **Assessing** function is enabled by the **Assessing System** which also acts on a project wide basis.

It is very important to note that a distinction has not been made in the **Project System** model on whether the **Systems/Process Development** process has to be *formal* or *informal*. Regardless of whether these systems are defined explicitly at the very outset, or develop iteratively in an informal manner, the effort for developing a methodology and implementation system has to be expended one way or the other, in order for project functions to be performed.

2.3.9.1.2. Resource Status

We also observe that for each of the resources a status and a cost attribute has also been defined. This information is monitored by the **Assessing** function which in turn generates the **Progress to-date / Forecast Report** which feeds back into **Enabling**.

2.3.9.2. Assessing

Within **Assessing** are the monitoring and assessment functions. These include:

- Monitoring
  - Resource Status - availability and utilization
  - Completion Status – task progress
  - Cost - level and basis of expenditure
  - Quality – adherence of work done to specifications
  - Regulatory Adherence – adherence of work done to regulations
  - Contextual Artifacts – variations in conditions
- Assessing and Forecasting
  - Progress - Actual vs. Planned
  - Expenditure vs. Estimate
  - Resource Utilization - Actual vs. Planned
  - Quality vs. Specifications
  - Performance vs. Regulations
  - Risk Assessment based on Contextual Variations

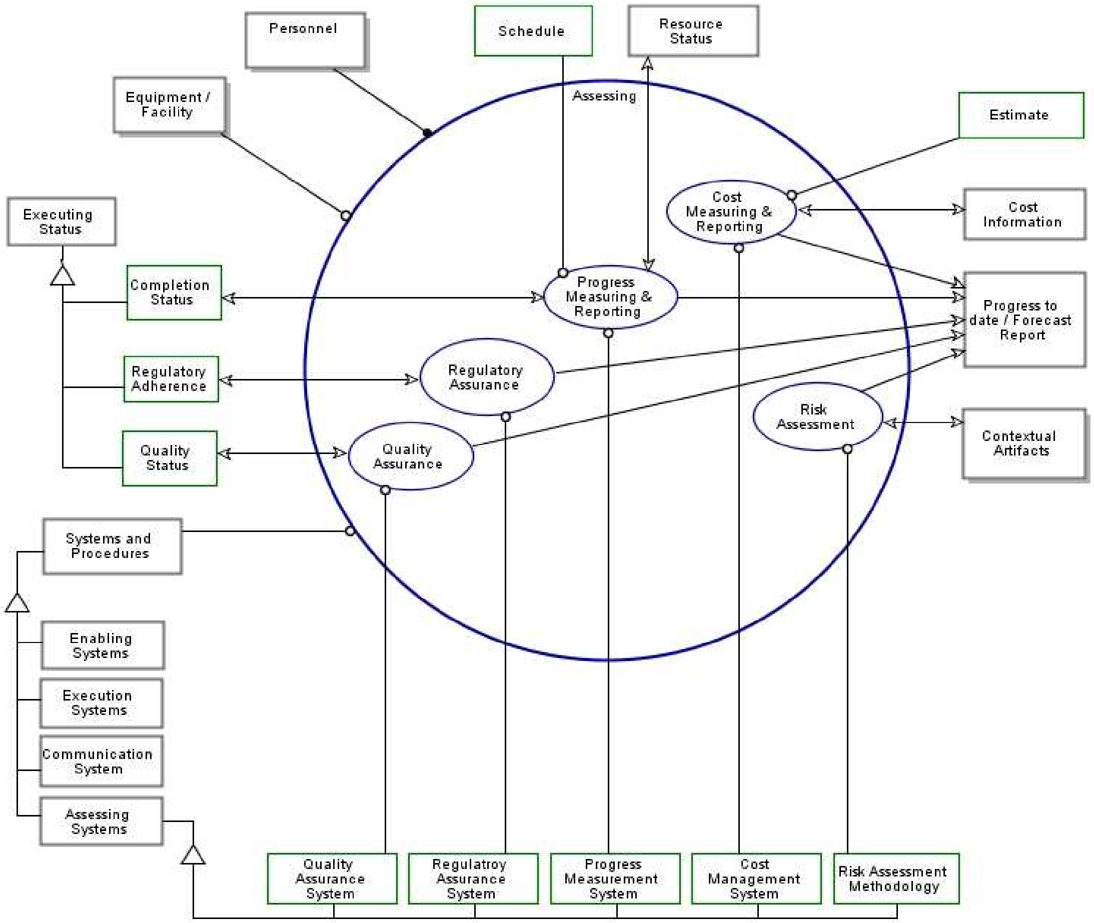


Figure 16: Assessing

- Cost Measuring & Reporting requires Cost Management System and Estimate
- Cost Measuring & Reporting affects Cost Information
- Cost Measuring & Reporting yields Progress to date / Forecast Report
- Progress Measuring & Reporting requires Progress Measurement System and Schedule

- Progress Measuring & Reporting affects Resource Status and Completion Status
- Progress Measuring & Reporting yields Progress to date / Forecast Report
- Regulatory Assurance requires Regulatory Assurance System
- Regulatory Assurance affects Regulatory Adherence
- Regulatory Assurance yields Progress to date / Forecast Report
- Risk Assessment requires Risk Assessment Methodology
- Risk Assessment affects Contextual Artifacts
- Risk Assessment yields Progress to date / Forecast Report
- Quality Assurance requires Quality Assurance System
- Quality Assurance affects Quality Status
- Quality Assurance yields Progress to date / Forecast Report.

2.3.9.2.1. Progress Measuring and Reporting

The **Progress Measuring and Reporting** is a critical function within **Assessing,** as it generates the **Progress to-Date / Forecast Report.** This element is defined in the model as a composite of the status information and its analysis, and is fed back to **Enabling**.

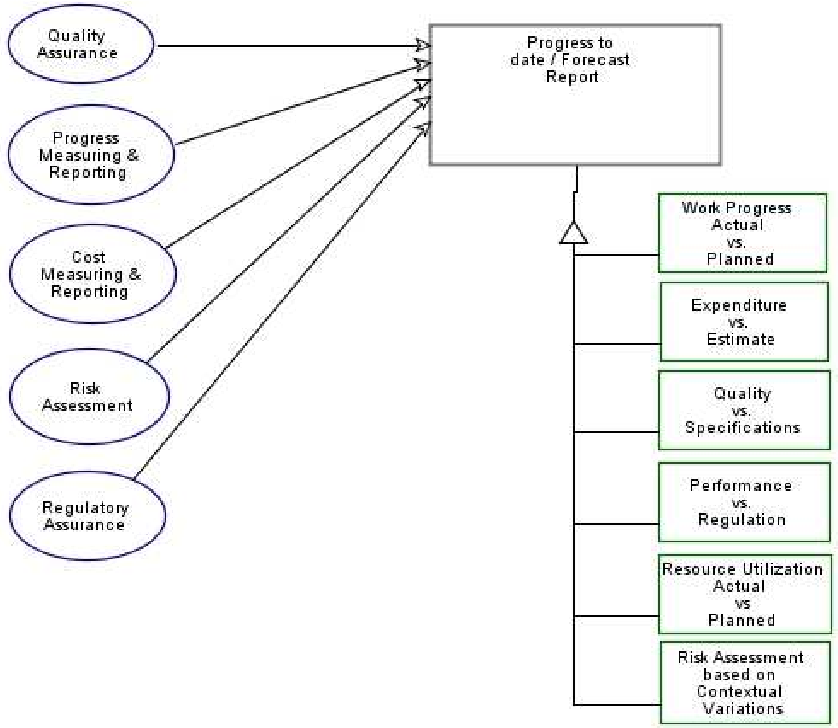


Figure 17: Progress to Date / Forecast Report

The fact that the **Progress Measurement System** is the instrument for the **Progress Measuring and Reporting** function is hardly surprising, but in addition the **Systems and Procedures** object has also been cited for this purpose. The connection of this superset object, which encompasses all of the **Instrument Systems** utilized on the project, demonstrates the necessity for each of these systems to integrate with project wide monitoring function in order for it to be effective.

Other points to note are the usage of **Instrument Systems** developed by the **Enabling** function to enable the **Assessing** functions, and also the ubiquity of the **Communication System** to the overall process.

2.3.10. Project Executing

This is the process of translating a **Need** into a **Product**. The formal structure of this **Product** and the specific tasks that must be carried out for this translation to occur can vary considerably depending upon the nature of the project. Nevertheless, it is possible to define three broad categories to classify these execution tasks:

- Requirements Engineering
- Designing
- Implementing

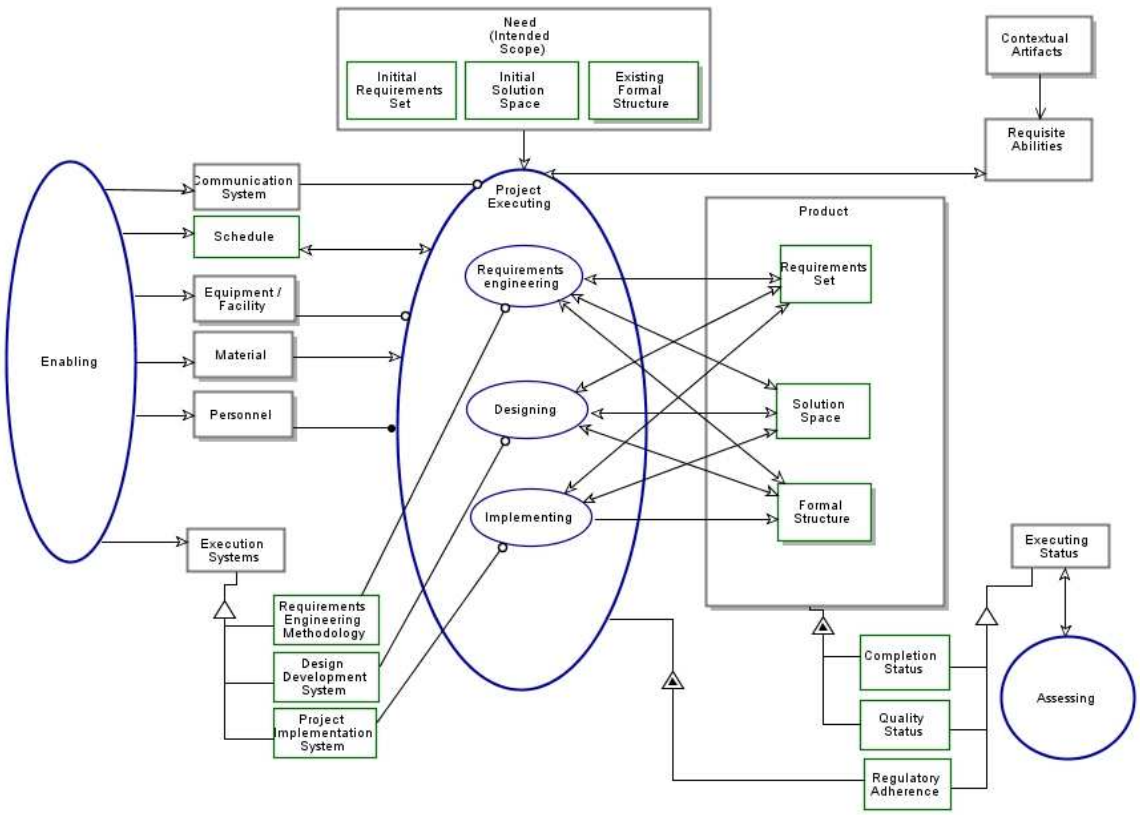


Figure 18: Project Executing

- Product exhibits Completion Status and Quality Status
- Completion Status is an Executing Status
- Quality Status is an Executing Status
- Contextual Artifacts relates to Requisite Abilities
- Existing Formal Structure is physical
- Personnel handles Project Executing
- Requirements Engineering Methodology is an Execution Systems
- Design Development System is an Execution Systems
- Project Implementation System is an Execution Systems

- Enabling yields Equipment / Facility, Schedule, Material, Personnel, Execution Systems, and Communication System
- Assessing affects Executing Status
- Project Executing exhibits Regulatory Adherence.

  Regulatory Adherence is an Executing Status.

  Project Executing consists of Designing, Requirements engineering, and Implementing
- Project Executing requires Communication System and Equipment / Facility
- Project Executing affects Schedule and Requisite Abilities
- Project Executing consumes Need (Intended Scope) and Material
- Project Executing zooms into Requirements engineering, Designing, and Implementing
- Requirements engineering requires Requirements Engineering Methodology
- Requirements engineering affects Formal Structure, Requirements Set, and Solution Space
- Designing requires Design Development System
- Designing affects Formal Structure, Requirements Set, and Solution Space
- Implementing requires Project Implementation System
- Implementing affects Requirements Set and Solution Space
- Implementing yields Formal Structure

It should be pointed out that it is not necessary that every project will have execution tasks that will fall into these categories. Nor is it implied that when more than one of these processes is present that they will occur sequentially or independently. As the *affect* links that join the **Project Executing** functions and the elements of the **Product** indicate they can potentially be highly interlinked.

It is also important to note that both the **Need** and the **Product** are modeled very similarly. They both consist of a:

- **Requirement Set**
- **Solution Space**
- **Formal Structure**

The key distinction between them however is that the set of information that constitutes the **Need** is a static representation of the initial intent; whereas the corresponding elements within the **Product** are all potentially dynamic during the course of the project. The degree of variation that may occur for the three elements will vary based on the project, however, between the three of them some variation must occur in order for it to be considered a project, and furthermore, all three must eventually attain a final state for the **Product** to be completed and the completion criteria of the project to be met.

The roles that the three types of **Project Executing** processes play in evolving the elements of the **Product** are described as follows:

2.3.10.1. Requirements Engineering

This is the process of evolving the design concept defined as the project **Need (Intended Scope)**, into the final design concept that will be espoused by the **Product**. While the specific details of how this occurs are studied in detail later in the thesis, suffice it to say at this stage that the elements that are affected by the process are the **Requirement Set** and the **Solution Space**. Nevertheless, information derived from the **Formal Structure** may feed back into the process as well.

The use of **Requirements Engineering** tasks within the **Project Executing** phase of a project indicates that at the very minimum there would be a need to evolve the **Solution Space**. This evolution may be a design refinement to address unfulfilled requirements, or the development of an implementation methodology for a design concept. Varying the **Solution Space** could potentially dictate a revision of the **Requirement Set** as well.

Not having a **Requirement Engineering** component would indicate that both the design concept and the implementation methodology are already established leaving only the formal structure to be developed.

2.3.10.2. Designing

This is the process of generating a *formalized* representation of the solution concept. **Designing** is used here in the traditional sense of developing drawings or models to record the concept formally and facilitate the implementation process. Once again it is not a necessary element, and it may be possible for **Implementing** to commence without a formalization of the **Solution Space**. That being said it is possible for the **Designing** processes to illicit new information or inconsistencies in the solution concept, or generate requirements that could feed back to the **Requirements Engineering** process.

2.3.10.3. Implementing

This is the process of converting a solution space concept into the **Formal Structure** of the **Product**. That is of course assuming that the project *requires* a **Formal Structure** for the final **Product**. It may be possible that all that is sought is a set of drawings, or a model depicting the solution concept. In which case there would cease to be a distinction between **Designing** and **Implementing**. It may also be purely a conceptual project which requires no **Designing** or **Implementing** and in which the project ends at the establishment of the final solution concept. As in the case with **Designing**, **Implementing** also has the potential of generating findings that may feed back into the **Requirements Engineering** process.

3. Project System Analysis

3.1. Model Analysis

To reiterate, this thesis set out to identify the systemic factors that influence the performance of a Project System as a whole, and to develop a systemic approach for strengthening any given project process, thereby mitigating the chances of being afflicted by failures.

The value of applying a systems analysis approach towards identifying where to focus our systems improvement efforts was manifold. Even though the model was developed on the basis of conventional project management wisdom, its ability to foster better cognition of the system as a whole was, for me personally at least, quite remarkable.

A key factor in achieving this clarity was the application of the solution neutral principle. Unencumbered by the restrictions of the typical organization structure it was easier to organize functions into natural groupings rather than by the formal elements that dictate their distribution on a real project. Furthermore, allowing the functions to dictate which objects to include in the model, resulted in the inclusion of both physical and informational inputs and outputs; as well as the instruments and agents required to enable them.

3.2. Project Cycles and Information flows

The model depicted the **Project System** as consisting of three main processes:

- Enabling
- Executing
- Assessing

Enabling generates the resources and systems, as well conducting the planning and scheduling, for the **Executing** work. The **Executing** function uses these inputs to develop the **Product**, while the **Assessing** function monitors all the processes and provides feedback for process improvement.

What is evident from the model is that in order to achieve all of this there are certain information flows that must be present:

- Execution can only be maintained if the assessment function is capable of keeping track of progress, quality, safety and external risks; and making it available to the enabling function in a timely fashion.
- Enabling must in turn be able to make decisions on strategy and communicate them to Execution
- Additionally Enabling also depends upon knowledge of available resources and their utilization
- Finally overall cost information must be assessed continuously and to ensure that the projects budgetary needs can be managed.

The flow of information therefore represents a critical factor in the performance of all of these functions. In fact, if improved it can be a means for achieving performance improvements in the Project System as a whole.

3.2.1. Information Types

The question then arises of what are the factors to consider when pursuing information flow efficiency.

First of all there is the question of the types of information that are relevant to the project:

3.2.1.1. Empirical or Formal Information:

Empirical information would be best described as factual information or data. It is generated via measurement or based on empirical evidence.

In the context of **Project Systems** this sort of information is essential for project planning and to gauge the actual performance vs. planned performance. It would include status and costs of all resources (manpower, material, equipment, facilities etc.) as well as task completion status and the resource utilization for each task. Certain quality indicators are also measureable when gauged against discretely defined specifications.

In the short term speedy access to such information is likely to improve the capability of the **Enabling** function to efficiently allocate the available resources thus improving overall performance. In the long term such data can be very useful in future planning and estimating work.

3.2.1.2. Heuristic or Informal information

Heuristic information is subjective in nature. It will manifest itself as ideas or opinions, and is the consequence of heuristic rather than empirical evidence. This type of information cannot be easily standardized and this intangible nature makes it less pre-disposed to technology enabled data management

From the perspective of **Project Systems**, it is equally as important as formal information, however, different processes are likely to have varying needs for the two types of information in order to be executed.

Processes which require a lot of decision making based on experience, or which are creative in nature, clearly depend on such information and require efficient channels for such information to flow. Examples would include planning, methodology development and design evolution. It may be argued that all of these processes could be improved with the application of empirical information but the reality is that in many situations empirical information is simply not available, and the process must rely on a heuristic approach to fill the gaps.

3.2.2. Information Flow Factors

Having defined the types of information another consideration is: what are the factors to consider with regards to information flow? And what implications does the type of information have on these factors?

Information theory[3] suggests that there are three factors to consider

- Bandwidth (Amount of Information)
- Noise (Quality of information)
- Delay (Time required for information transfer)

3.2.2.1. Bandwidth

The source of Empirical Information is the measuring function. Therefore the bandwidth will partly depend on the capacity of the system utilized for measuring the data. It can also be dependent upon the measuring system having sufficient access to the article being measured.

[3] Verdu, Sergio. "Information Theory: Fifty Years of Shannon theory". IEEE Press. (2000)

The source of Informal Information is the stakeholders that possess this information. Their experience and expertise will determine how much information is available for transfer.

However, bandwidth is not only affected by information sources but by information channels as well. These capacity of these channels can be a limiting factor to how much of the available information can be transferred.

3.2.2.2. Noise

Like Bandwidth, information Quality can also be affected by source issues as well as channel issues. At source it is a question of the measuring system performance for data collection, and a question of stakeholder qualifications for informal information.

Additionally, in both cases the channels can contribute to information loss or even information corruption.

3.2.2.3. Delay

Delay in information transfer is purely a channel issue. It reflects the efficiency of the information transfer systems being utilized on a project, and the barriers within these systems that may impede the flow. Its impact can be felt on both types of information

3.2.3. Asymmetric Information and Transaction Costs

Collectively the factors related with information flow bring forth the concept of information asymmetry. Information asymmetry exists when relevant information is present, but is not available to those who need it. This can be due to limited channel capacity, loss of information during transfer or late arrival of the information. The result however is the same; the information is not available to those who need it when they need it.

In the context of Project Systems we established earlier that the performance of project processes depends on certain information being available in a timely manner. This implies that there is an inverse relationship between project performance and the degree of information asymmetry; and that the consequence of information asymmetry is that the potential benefits that could have been derived from these processes are not actualized.

A parallel can be drawn between this phenomenon and Transaction Cost Economic theory. Ronald Coase, who pioneered Transaction Cost Economics proposed that, "… all potential gains from trade would be realized but for the costs of reaching and enforcing an agreement. Hence in comparing alternative institutional arrangements, the focus of attention becomes the nature and size of the barriers preventing transactors from securing those gains"[4].

Clearly one of the barriers preventing a project process from securing all of its potential gains is information asymmetry. The question then is: what are the institutional arrangement (or formal structure) factors that are impeding the flow of information?

It would be worth while to note at this point that rapid detection of deficiencies in a project also represents an asymmetrical information problem, it is therefore evident that improvements in this area could address two of the thesis objectives:

- identifying means to improve problem detection
- identifying means to improve overall project performance

Unfortunately, this insight is only part of the answer. The question still remains of *how* to improve the flow of information. This can be addressed via the third objective of this thesis; which is to develop a systems approach to process improvements that can be applied to any aspect of a project system.

3.3. Systems Approach to Process Improvements

Referring back to the **Project System** model we note that the formal elements of the system were described as **Contextual Artifacts**. Within these artifacts, the **Need** and

[4] Coase, Ronald. "The Nature of the Firm". Economica. (1937)

the **Environment** encompass all of the information pertaining to the project's objectives and the context within which these objectives are to be met. Obviously, they have a fundamental impact on every process within the **Project System**; however, they always remain firmly outside of the project's control.

The two artifacts where the project does have flexibility to make variations are **Project Organization** and **Agreements.** The structure and composition of both of these artifacts is entirely within the domain of the **Project Managing** function to define as needed. Failure to utilize this flexibility to establish an organization, and define agreements, that can specifically address a project's unique needs and environmental factors, will ultimately determine its degree of success or failure.

The **Project System** model depicted the effectiveness of the project as a whole, and by extension, every process that exists within the project, to be dependent upon the presence of **Requisite Abilities.** Furthermore, it was stated that it is the **Contextual Artifacts** that determine whether or not the **Requisite Abilities** are present, and to what extent.

We can now refine this concept by stating that project success depends upon being able to define the **Project Organization** and its associated **Agreements**, in such a way that they can *supply* the **Requisite Abilities** which are *demanded* by the **Need** and the **Environment**.

- **Requisite Abilities <u>Demand</u> Side Contextual Artifacts :**
    - Need and Environment
- **Requisite Abilities <u>Supply</u> Side Artifacts:**
    - Project Organization and Agreements

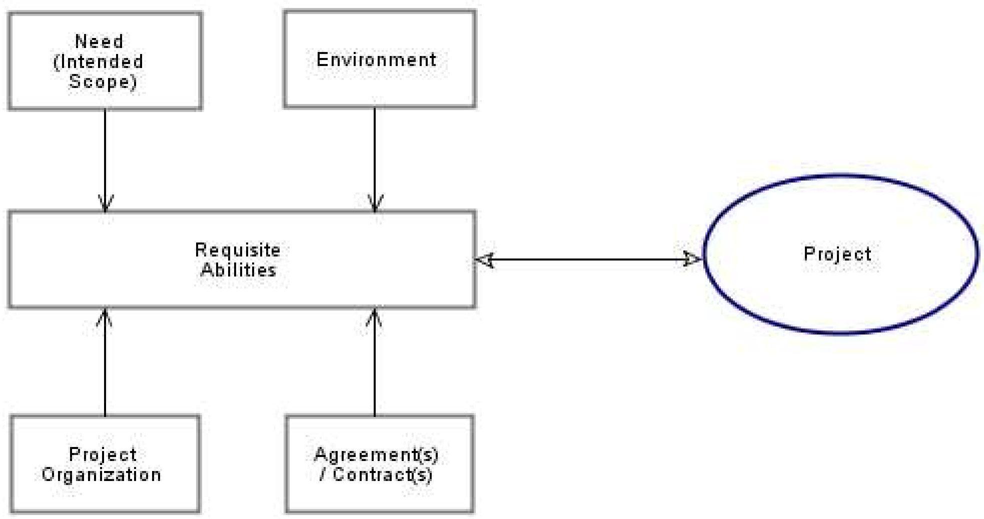


Figure 19: Demand and Supply Side Contextual Artifacts

This concept can essentially be focused on to every process that exists within the **Project System**. After all, the purpose of any given process within the Project System is to fulfill some aspect of the project's **Need**. Furthermore this purpose must be fulfilled in the context of the **Environment** in which the project is being pursued. Collectively these two factors will define which specific **Requisite Abilities** will be needed to enable this particular process to fulfill its purpose. However, it will depend upon certain elements within the **Project Organization** and the **Agreements** being designated to ensure that these needed **Requisite Abilities** are actually present. The effectiveness of each process therefore depends upon first understanding all of its **Requisite Abilities** needs, and then fulfilling them. The collective strength of these abilities will determine how well the process performs. Conversely, a deficiency in even a single required ability may cause a process to fail. This lays the foundation for a **Systems Approach to Process Improvements**.

The **Requisite Abilities** that were defined in the **Project System** model are explained as follows:

- **Capability / Capacity to Work** is essential for every process to fulfill its primary purpose and therefore must always be present. The **Need** and the **Environment** are the determinants of the purpose of each process, while resources within the **Project Organization** provide the capacity to execute it. Additionally elements within the **Agreements** that govern these resources may influence their ability to execute the task as well. It should also be noted that elements within the **Need** and **Environment** may place limitations on the flexibility of the **Project Organization** and **Agreements** as well
- **Ability to Incentivize Work** is necessary for most processes because inducing an individual to perform a task typically requires some form of motivation. The **Need** and the **Environment** will play a role in determining the level of incentive required as well as place limits on the maximum amount of incentives that can be disbursed; while the transaction itself would be enshrined within the **Agreements** between the parties contracting the work.

- **Ability to Communicate** is required because it is the means for seeking and receiving instructions on how to execute the work. The **Need** will determine how much communication is necessary for a particular process, however, it is elements within the **Project Organization** that are responsible for enabling this communication. The **Environment** can play a significant role in facilitating or impeding this flow of information as can elements within **Agreements.** Additionally **Agreements** can also serve as a means for transferring instructions, i.e. act as enablers.
- **Ability to Monitor Status** is needed to ensure that a process is proceeding according to expectations. The degree, and in some cases even the necessity, for monitoring will largely be determined by the **Need**. Elements within **Project Organization** will be responsible for enabling monitoring to occur. A significant factor that affects the ability to monitor is the accessibility of the monitoring function to the process in question. The accessibility can be affected by a range of elements within **Project Organization**, the **Environment** and **Agreements**
- **Ability to Make Decisions** refers primarily to the authority and the methodology needed for making decisions. It is of course only relevant to those processes which entail decision making in order to function. Referring back to transaction cost theory, this ability is directly concerned with "the costs of reaching and enforcing an agreement". The **Need** will determine whether or not a particular process entails any decision making. The **Environment** can play a significant role in determining the willingness of

project principals to delegate such authority; while elements within the **Project Organization** and **Agreements** determine whether this ability is available to the relevant agents or not.

Collectively these relationships are depicted as follows:

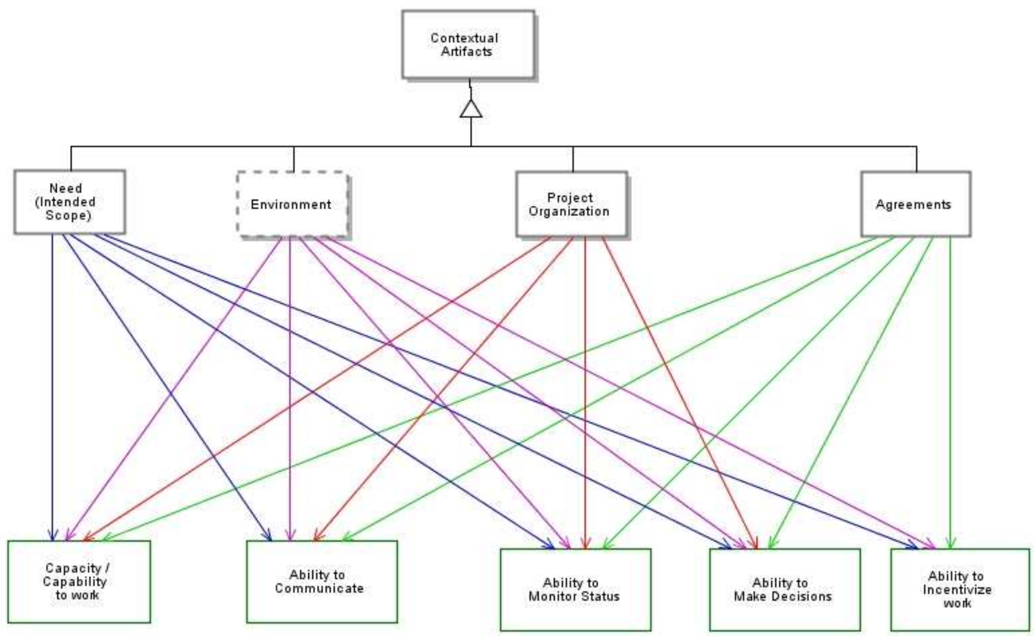


Figure 20: Contextual Artifacts - Requisite Abilities

It is important to understand that the ramifications of each ability will be unique for every process. In other words the specific skill needed, the amount and type of incentives required, the appropriate communication and monitoring mechanisms that should be employed, and the degree of decision making authority that should be delegated have to be determined for every process individually.

So far the basic framework of how the **Contextual Artifacts** relate to the **Requisite Abilities** has been laid out. However, to derive any practical value from this approach it is necessary to scrutinize these relationships at the component level of each artifact.

3.3.1. Demand Side Contextual Artifacts

The artifacts which determine which **Requisite Abilities** are needed for a process are the **Need** and the **Environment**. In addition to this, elements within these two artifacts can also place limits on which Supply Side artifacts may be utilized; the most prominent examples being **Funding Limits** and **Funding Availability**, which may designate certain Supply Side options as being too expensive.

3.3.1.1. Need (Intended Scope)

Since this is a generalized approach towards improving an unspecified process the specifics of the **Initial Requirement Set**, **Initial Solution Space** and **Existing Formal Structure** are not available to us.

However, we are in a position to conduct an analysis on the attributes of the **Need** artifact. The attributes that were defined for the Need element in the Project System model were as follows:

- Scope size
- Degree of evolution
- Degree of modularity
- Novelty of the work
- Number of external stakeholders
- Funding Limits
- Expected period of performance

The majority of these attributes have the affect of defining the purpose of a process as well as its required performance. The exceptions are **Funding Limits** and **Expected period of Performance** which influence required performance. Additionally **Funding Limits** can directly impact the Supply Side artifacts as well.

Correlating these attributes with the **Requisite Abilities** of Project Management, elicits the following relationships:

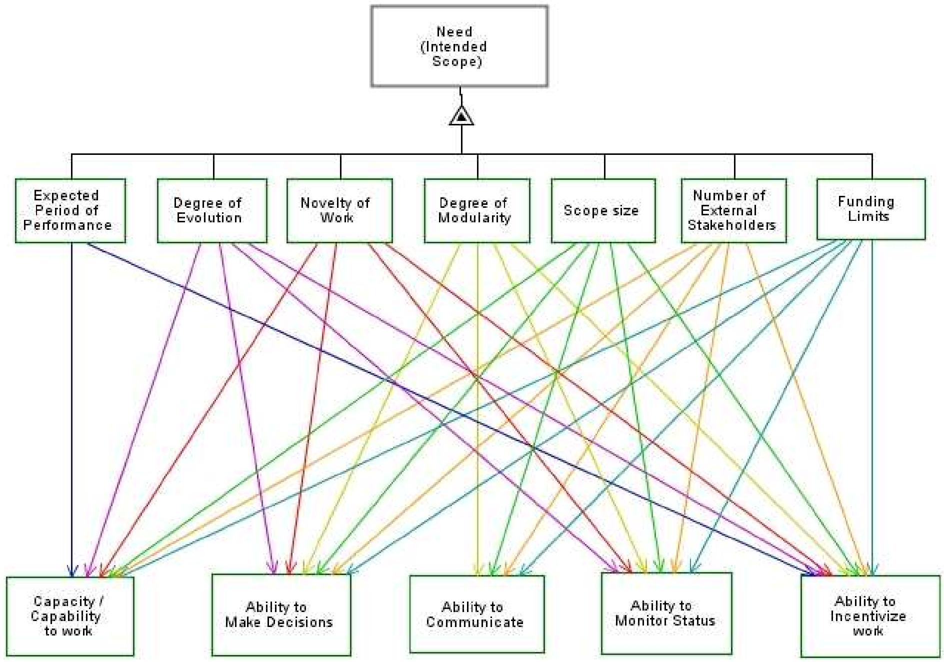


Figure 21: Need - Requisite Abilities

- **Capacity and Capability**

  - Funding Limits relates to Capacity / Capability to work
  - Scope size relates to Capacity / Capability to work
  - Expected Period of Performance relates to Capacity / Capability to work
  - Number of External Stakeholders relates to Capacity / Capability to work
  - Degree of Evolution relates to Capacity / Capability to work
  - Novelty of Work relates to Capacity / Capability to work

- **Ability to Incentivize Work**
  - Degree of Evolution relates to Ability to Incentivize work
  - Scope size relates to Ability to Incentivize work
  - Funding Limits relates to Ability to Incentivize work
  - Expected Period of Performance relates to Ability to Incentivize work
  - Number of External Stakeholders relates to Ability to Incentivize work
  - Degree of Modularity relates to Ability to Incentivize work
  - Novelty of Work relates to Ability to Incentivize work

- **Ability to Communicate**
  - Funding Limits relates to Ability to Communicate
  - Scope size relates to Ability to Communicate
  - Number of External Stakeholders relates to Ability to Communicate
  - Degree of Modularity relates to Ability to Communicate

- **Ability to Monitor Status**
  - Funding Limits relates to Ability to Monitor Status
  - Scope size relates to Ability to Monitor Status
  - Degree of Modularity relates to Ability to Monitor Status
  - Degree of Evolution relates to Ability to Monitor Status

- Novelty of Work relates to Ability to Monitor Status
- Number of External Stakeholders relates to Ability to Monitor Status

- **Ability to Make Decisions**

  - Degree of Evolution relates to Ability to Make Decisions
  - Number of External Stakeholders relates to Ability to Make Decisions
  - Scope size relates to Ability to Make Decisions
  - Funding Limits relates to Ability to Make Decisions
  - Novelty of Work relates to Ability to Make Decisions
  - Degree of Modularity relates to Ability to Make Decisions

3.3.1.2. Environment

The Project System model defined the following attributes of the Environment that can potentially influence a project:

- Physical Site Conditions
- Regulations and Legal considerations
- Resource Availability
- Funding Availability
- Work Availability

- Competitive Environment

Resource Availability, Funding Availability and **Work Availability** do not affect the process directly, but can place limits on the instruments and agents that may be utilized to execute the process. **Physical Site Conditions**, **Regulations and Legal considerations** and **Competitive Environment** can also limit agent and instrument utilization, but they have a direct impact in defining the required performance of a process as well.

Correlating these attributes with the **Requisite Abilities** we see the following relationships.

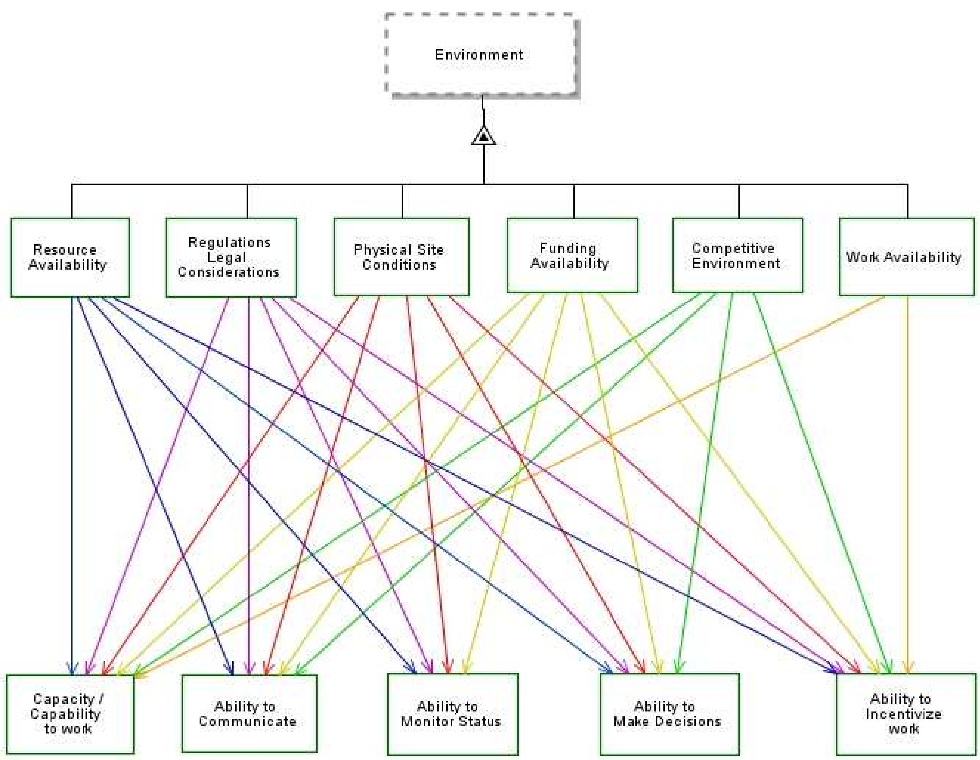


Figure 22: Environment - Requisite Abilities

- **Capacity and Capability**
  - Competitive Environment relates to Capacity / Capability to work
  - Work Availability relates to Capacity / Capability to work
  - Physical Site Conditions relates to Capacity / Capability to work
  - Regulations Legal Considerations relates to Capacity/ Capability to Work
  - Resource Availability relates to Capacity / Capability to work
  - Funding Availability relates to Capacity / Capability to work.

- **Ability to Incentivize Work**
  - Work Availability relates to Ability to Incentivize work
  - Competitive Environment relates to Ability to Incentivize work
  - Physical Site Conditions relates to Ability to Incentivize work
  - Regulations Legal Considerations relates to Ability to Incentivize work
  - Resource Availability relates to Ability to Incentivize work
  - Funding Availability relates to Ability to Incentivize work

- **Ability to Communicate**
  - Competitive Environment relates to Ability to Communicate
  - Physical Site Conditions relates to Ability to Communicate
  - Regulations Legal Considerations relates to Ability to Communicate

- Resource Availability relates to Ability to Communicate
- Funding Availability relates to Ability to Communicate

- **Ability to Monitor Status**
  - Physical Site Conditions relates to Ability to Monitor Status
  - Regulations Legal Considerations relates to Ability to Monitor Status
  - Resource Availability relates to Ability to Monitor Status
  - Funding Availability relates to Ability to Monitor Status

- **Ability to Make Decisions**
  - Resource Availability relates to Ability to Make Decisions
  - Regulations Legal Considerations relates to Ability to Make Decisions
  - Physical Site Conditions relates to Ability to Make Decisions
  - Competitive Environment relates to Ability to Make Decisions
  - Funding Availability relates to Ability to Make Decisions

3.3.2. Supply Side Contextual Artifacts

3.3.2.1. Project Organization

The **Project Organization** was defined in the **Project System** model as being constituted of the following elements and attributes:

- Personnel
- Equipment / Facility

- Systems and Procedures
- Organizational Structure

Correlating the elements and attributes of the **Project Organization** with the **Requisite Abilities** yields the following:

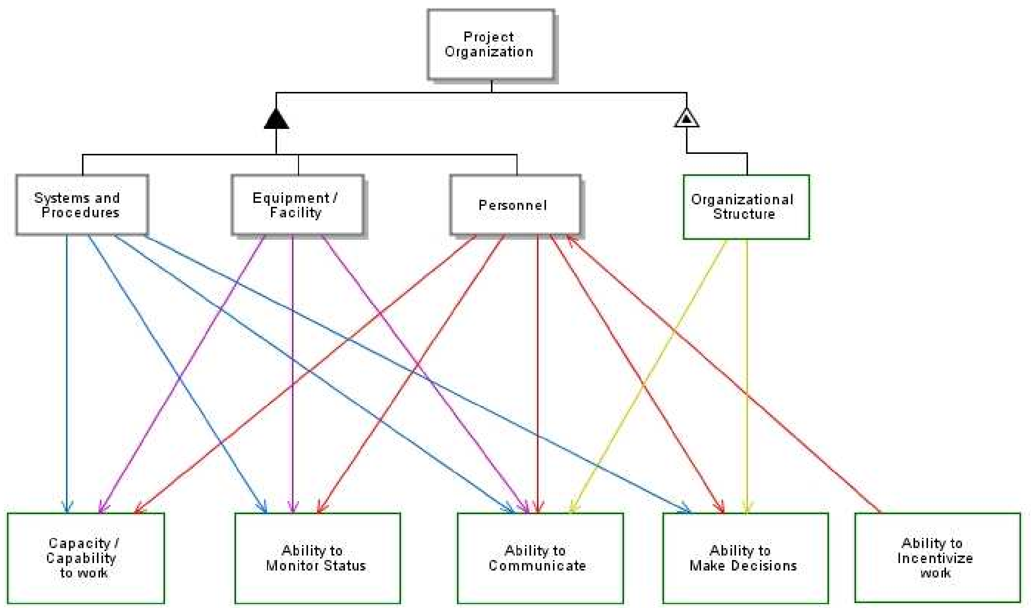


Figure 23: Project Organization - Requisite Abilities

3.3.2.1.1. Personnel

The **Personnel** element of the **Project Organization** reflects the following impacts:

- Personnel relates to Capacity / Capability to work

- Personnel relates to Ability to Communicate
- Personnel relates to Ability to Monitor Status
- Personnel relates to Ability to Make Decisions

Important attributes of **Personnel** include:

- Experience
- Training
- Quantity

It is interesting to note that commonly, the primary criteria utilized for hiring personnel is a candidate's skill in a particular field, which relates only to the **Capacity/Capability to Work**. One might argue that certain positions do not require communication, monitoring or decision making, and that proficiency in a basic skill is all that is needed. Unfortunately, even for positions with job requirements that go well beyond just a technical skill it is not uncommon to see no tangible change in the hiring approach.

From a systems perspective it is important to recognize that for processes that require the abilities of communication, monitoring and decision, it is very important to provide the agents that are adept at fulfilling these roles. This can be achieved by hiring personnel that are experienced in these roles, or through proper training, or even by constituting a team which can collectively fulfill all the necessary roles.

3.3.2.1.2. Equipment/Facility

The **Equipment / Facility** element of the **Project Organization** reflected the following impacts:

- Equipment / Facility relates to Capacity / Capability to work
- Equipment / Facility relates to Ability to Communicate
- Equipment / Facility relates to Ability to Monitor Status

The critical attributes of **Equipment/Facility** to consider are:

- Quality
- Ease of Use
- Suitability
- Capacity

Appropriate equipment and facilities are obviously an important factor in enabling the **Requisite Abilities** needed for a process. In most real world settings, barring any funding or availability issues, the attempt is usually made to find the best tools possible for the task at hand; particularly those which relate directly with **Capacity / Capability to work.** With respect to the **Ability to Communicate** and the **Ability to Monitor Status**, however, it would be worthwhile to make a point here.

Information transfer in general was earlier differentiated on the basis of:

- Formal information transfer
- Informal information transfer

Typically, however, in an actual project setting, formal information management tends to be better served in terms of equipment and facilities, because of the tangible nature of the information. With respect to informal communication, however, the needs may be less evident, and the potential of using enabling technologies to promote such interactions is often undervalued.

Research work by Prof. Tom Allen[5] has indicated the importance of establishing personal relationships between team members as an enabler for interaction and collaboration; which would suggest that focusing exclusively on formal information enablers at the expense of informal information enablers may actually be detrimental strategy.

His work also illustrates how work facility layout and architecture can be leveraged to promote greater bonding amongst members of an organization, as can the use of interaction enabling technologies such as video conferencing, and virtual design boards.

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[5] Allen, Thomas. Henn, Gunter. "The Organization and Architecture of Innovation". Elsevier Inc. (2007)

It is important to note that the need for these enablers increases if environmental factors such as geographical dispersion of team members, or even physical separation of departments within a single compound, are acting as a barriers to the establishment of relationships, or to informal information transfer in general.

3.3.2.1.3. Systems and Procedures

The **Systems and Procedures** element of the **Project Organization** reflected the following impacts:

- Systems and Procedures relates to Capacity / Capability to work.
- Systems and Procedures relates to Ability to Communicate
- Systems and Procedures relates to Ability to Make Decisions
- Systems and Procedures relates to Ability to Monitor Status

If we refer to the details regarding **Systems and Procedures** within the **Project System model** it is important to note that there are two aspects of **Systems and Procedures** that are relevant to fulfilling **Requisite Abilities**:

- Instrument Systems
- Project Wide Systems

3.3.2.1.3.1. Instrument Systems

Instrument Systems are the procedures and methodologies that define the execution of individual processes. Each **Instrument System** will consist of a set of procedures which can be correlated to the **Requisite Abilities**:

- Functional Procedure
  - ↔ Capacity / Capability to work
- Participant / Instrument Involvement
  - ↔ Capacity / Capability to work
- Delegation of work
  - ↔ Capacity / Capability to work
- Information Sharing Protocols
  - ↔ Ability to Communicate
  - ↔ Ability to Monitor Status
- Decision Making Protocols
  - ↔ Ability to Make Decisions
- Authority Delegation
  - ↔ Ability to Make Decisions

In an earlier discussion on **Instrument Systems** it was noted that the **Project System** model does not specify whether these systems are generated through a formal approach to their development and maintenance, or are simply an after-the-fact representation of how a particular project process was pursued.

The main benefit of a formal approach of course is that it reduces the likelihood of critical considerations being ignored. Information and interaction related abilities in particular are always at risk of being managed in an ad hoc manner, far more so than any procedure that is needed for the primary purpose of the function.

However, even if a formal methodology is developed that does not guarantee it will be the only factor influencing the process. As further discussion of artifact elements will demonstrate there are a wide range of factors that can influence the information and interaction related abilities.

Understanding these other impacts is therefore an important consideration when crafting information protocols. On the other hand, failure to craft formal protocols will mean that these other elements will end up being the governing factors.

3.3.2.1.3.2. Project Wide Systems

The other aspects of **Systems and Procedures** to consider are the project wide **Communication System** and **Assessing System**. These systems play the role of interfacing with all the project processes, and act as integrators and exchanges for the generated and sought-after information.

The importance of information flow as a critical factor in overall Project performance has already been established. So it is safe to say that both of these **Project Wide Systems** can be expected to have far reaching implications for the **Requisite Abilities.**

However, in light of the previous discussion on **Instrument Systems** it is important to understand that information flow must be enabled at both the process level and the project wide level in order to be successful. Furthermore it is the process specific needs for information that must dictate the nature of the project wide systems that are adopted.

3.3.2.1.4. Organizational Structure

The **Organizational Structure** attribute of the **Project Organization** relates with the following **Requisite Abilities**:

- Organizational Structure relates to Ability to Communicate
- Organizational Structure relates to Ability to Make Decisions

It is important to understand that over here **Organizational Structure** is not necessarily limited to just a single firm. Rather it refers to how all of the entities involved in a project would be structured regardless of whether they are independent firms or departments within a single firm.

According to G. Carroll and D. Teece "Transaction-Cost economics recast the firm as a governance structure, one among several alternative ways in which production and exchange might be organized".[6] In this statement they make a clear distinction between inter-firm and intra-firm transactions as being alternative methodologies. In contrast, the structure presented in this thesis argues that in the project setting the Project Managing function defines a governance structure that extends to all entities involved in the project regardless of whether they are departments or independent firms.

This governance structure, or project wide organizational structure, plays a significant role in defining the transaction costs associated with these entities interacting with one another as required by the project. These costs manifest themselves as barriers to the flow of information, and this extends into the ability to integrate these recourses (or entities) to achieve

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[6] Carroll, Glenn. Teece, David. "Firms Markets and Hierarchies". Oxford University Press. (1999)

the project goal (product), as well as the decision making and monitoring functions.

Primarily the impact of the **Organizational Structure** is on the ability of stakeholders to communicate and to interact. However, in contrast to some of the preceding elements the impact of the **Organizational Structure** tends to be relatively implicit rather than explicit. Its affect is also liable to be greater in the absence of any formal protocols defining information flow or interaction.

3.3.2.2. Agreements

Crafting the agreements and the contracts which govern the stakeholder interactions is the other area in which Project Management has the freedom act in accordance with the needs of the project.

The elements of interest that were previously defined for this artifact include:

- Definitions and Specifications
- Effective Dates and Period of Performance
- Processes and Procedures
- Roles and Responsibilities
- Allocation of Risk
- Incentives and Incentive Structure

Correlating these elements with the **Requisite Abilities** yields the following:

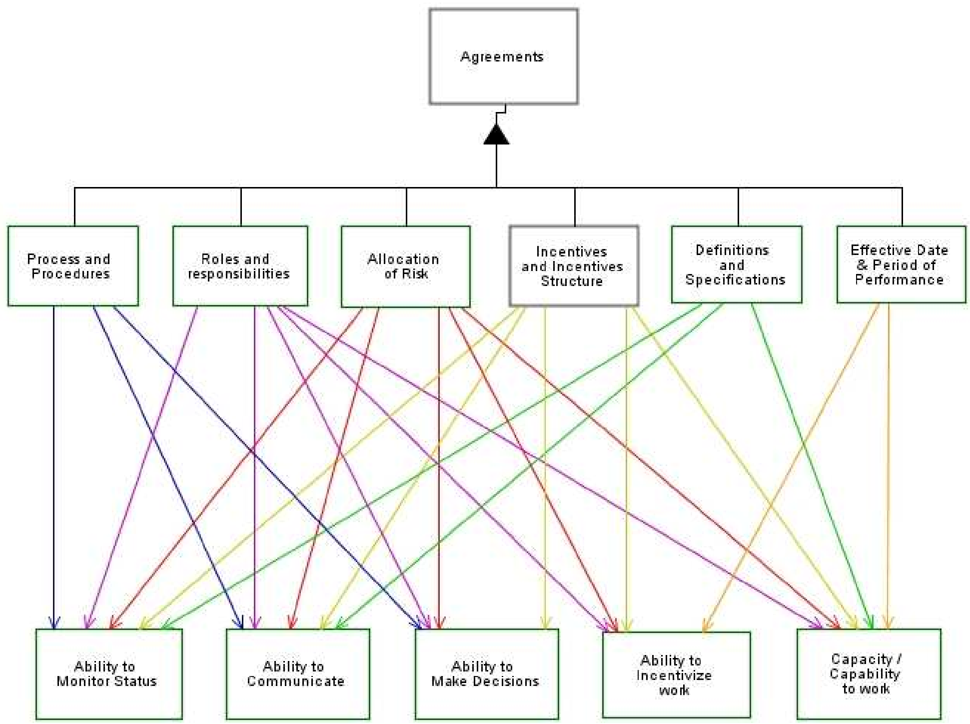

Figure 24: Agreements - Requisite Abilities

Much in the same way that the inter and intra-firm organization structures have not been segregated in the Project System model, the **Agreements** artifact is also inclusive of all agreements between project entities regardless of whether they are formal/informal or inter/intra firm.

However, this does not imply that the transaction cost is unaffected by the degree of formality or the nature of the agreeing parties. On the contrary transaction-cost economics theorizes that the primary motivation for forming multi-functional firms in the first place is the potential reduction in transaction costs. This is based on the principle that formal agreements between independent entities are likely to entail a higher administrative effort to maintain than the informal, and also relatively flexible, relationships that can be established between departments of a single firm.

3.3.2.2.1. Effective Dates and Period of Performance

- Effective Date & Period of Performance relates to Capacity / Capability to work.
- Effective Date & Period of Performance relates to Ability to Incentivize work

The **Effective Date and Period of Performance** is an important element of defining the expected performance on the scope of work defined in the agreement. Accordingly it impacts the **Capacity/Capability to work** as well as the **Ability to Incentivize work**

Of course it must be correlated with and remain within the **Expected Period of Performance** as defined in the **Need.**

3.3.2.2.2. Definitions and Specifications

- Definitions and Specifications relates to Ability to Communicate
- Definitions and Specifications relates to Ability to Monitor Status
- Definitions and Specifications relates to Capacity / Capability to work

The **Definitions and Specifications** play an important role in establishing a clear understanding of the scope of work and consequently can directly impact the **Capacity/Capability to work**. Clearly this can play an important role in facilitating the flow of instructions and queries. In terms of monitoring it is the specifications that provide the basis of assessment.

3.3.2.2.3. Processes and Procedures

The **Processes and Procedures** component of **Agreements** relates to:

- Processes and Procedures relates to Ability to Communicate
- Processes and Procedures relates to Ability to Make Decisions
- Processes and Procedures relates to Ability to Monitor Status.

The **Processes and Procedures** component of **Agreements** should not be confused with the **Systems and Procedures** element of the **Project Organization**. The procedures being referred to here are specifically those that govern how entities that are party to the agreement interact with one another.

It was noted previously that in the absence of a formalized Information Protocols within the **Instrument Systems**, other factors would be more likely to govern the efficiency of the interactions between stakeholders. The most prominent amongst these are the **Processes and Procedures** which are defined within the agreements between the stakeholders. In the event that the stakeholders are independent firms the importance of this element becomes even higher because it is enshrined in a legal contract, to the extent that it may overshadow all other information sharing protocols.

Furthermore, formal contracts entail legal considerations that may not necessarily be even noted explicitly within their text. Nevertheless they still manifest themselves implicitly in the protocols of engagement between the parties. Needless to say this has significant implications on the transaction costs associated with these interactions.

3.3.2.2.4. Roles and Responsibilities

The **Roles and Responsibilities** component of **Agreements** relates with the following **Requisite Abilities**:

- Roles and responsibilities relates to Capacity /Capability to work

- Roles and responsibilities relates to Ability to Communicate
- Roles and responsibilities relates to Ability to Make Decisions
- Roles and responsibilities relates to Ability to Incentivize work
- Roles and responsibilities relates to Ability to Monitor Status

The **Roles and Responsibilities** element refers to the respective obligations that project participants take responsibility for when they make an agreement.

The primary benefit of defining **Roles and Responsibilities** within an agreement is that it enables these roles to be fulfilled. In this sense the formal inclusion of these **Roles and Responsibilities** within the agreement is an act of authorization or delegation. This is important where there are a large number of participants amongst whom the total work must be distributed. In this case, clear authorization of specific scopes of work will avoid contention between the parties. Explicit distribution of all aspects of the work also ensures that nothing is overlooked and the project does not suffer from underperformance in certain areas. This is particularly relevant with respect to the **Capacity /Capability to work**, the **Ability to Communicate,** and the **Ability to Monitor Status.**

The **Ability to Make Decisions** can be influenced by the explicit delegation of approval authority to specific participants.

Finally, the assignment of certain **Roles and Responsibilities** within the scope of work can also serve as motivation, or an act of incentivizing. The desired outcome of this approach is that it is likely to yield better performance. Examples include performance warranties, quality assurance or safety assurance.

It is worth noting that in some scenarios, the assignment of a role can have a potentially negative impact if the party made responsible does not exercise sufficient control over factors related with the fulfillment of the role. In such a scenario instead of acting as an incentive the assignment of an obligation ends up increasing the participant's risk. This phenomenon is covered in greater detail within the **Allocation of Risk** section.

Finally there may be some **Roles and Responsibilities** that may not be expressly stated within the agreement but which the participants are bound to due to regulatory or legal requirements. Examples include fiduciary duty.

3.3.2.2.5. Incentives, Incentives Structure and Allocation of Risk

The **Incentives and Incentives Structure** component of **Agreements** relates to:

- Incentives and Incentives Structure relates to Capacity /Capability to work
- Incentives and Incentives Structure relates to Ability to Incentivize work
- Incentives and Incentives Structure relates to Ability to Communicate
- Incentives and Incentives Structure relates to Ability to Monitor Status
- Incentives and Incentives Structure relates to Ability to Make Decisions

The fact that **Incentives and Incentives Structures** relate to the **Ability to Incentivize work** is hardly surprising. However, the relationship with all the other abilities has to do with the utilization of agents to enable them. Any aspect of a process that requires agents to do part of the work will require some form of incentive.

Incentives can be both tangible and intangible and can include the following types:

- Monetary
- Service in-trade
- Access to technology/knowledge
- Market Access
- Future work
- Opportunity to gain experience

The most common type of course is monetary, and this is also the one focused on in this thesis.

While the **Incentives** are the actual benefit gained by execution of scope the **Incentive Structure** defines the *basis* of compensation. While there can be some variations in practice the two most common types are:

- Fixed Price – Total Price is pre-negotiated and payment is made on the basis of earned value
- Cost Plus – Contractor is paid the cost of execution plus either a percentage of cost or a fixed fee as margin

The **Incentive Structure** that is applied can have a significant impact on the **Allocation of Risk**.

The **Allocation of Risk** element of **Agreements** correlates to **Requisite Abilities** as follows:

- Allocation of Risk relates to Capacity /Capability to work
- Allocation of Risk relates to Ability to Incentivize work
- Allocation of Risk relates to Ability to Communicate
- Allocation of Risk relates to Ability to Monitor Status
- Allocation of Risk relates to Ability to Make Decisions

To understand **Allocation of Risk,** it important to first differentiate between Project Wide Risk and Individual Project Participant Risk.

Project wide risk is largely determined by the **Need** and the **Environment**; practically all of the attributes and elements within these two **Contextual Artifacts** can contribute to the risk. Furthermore, in addition to assessing their contribution at the start of the project, the possibility of variations amongst these factors during the course of the project also remains an ongoing concern.

Individual Project Participant Risk is the risk burden that a particular participant in a project is carrying. This is primarily a function of the Project Wide Risk, however, the variability of impact of the same risk on different participants also needs to be kept into consideration.

The main factors that can come into play in the allocation of risk are:

- Natural inclination amongst all participants to minimize the risk burden that they are carrying.
- Prevailing market conditions – buyers market vs. sellers market
- Legal and Regulatory liability considerations
- The ability of a participant to manage factors influencing the risk
- Expected Value – Possible Incentive vs. possible risk
- Capacity to absorb losses – individual risk impact
- Risks as a form of motivation

This allocation is formalized within the agreement between the parties that are participating in the project. The default owner of all the risk is the project owner. However, being the party that issues all the contracts affords the owner the opportunity to transfer portions of the risk to other participants. The natural inclination is to shift as much as possible in this manner. Those issues that entail financial risks or legal/regulatory liabilities are often the biggest contenders for distribution.

The willingness of the contractors to accept these risks is in part affected by prevailing market conditions, which impacts their desperation to acquire the work. They may also be willing to accept the risk on the basis that when viewed in the light of the associated incentives, they perceive the expected value to be favorable. Also, they may deem the risk to be manageable because they have expertise and experience that can prevent the risk from being actualized, or because they possess the capability to mitigate the risks through influence on its driving factors, or even because they possess contingencies that would enable them to absorb the potential impacts of the risk.

As was noted previously the **Incentive Structure** is one of the ways in which risk allocation can manifest it self. A Fixed Price Contract places the majority of the burden associated with scope ambiguity and changes in conditions upon the contractor; whereas a Cost-plus Contract guarantees the contractor both reimbursement of cost as well as their margin.

The allocation of **Roles and Responsibilities** also plays a factor in risk allocation. A role which has an ambiguous scope of work clearly contains risks, particularly when coupled with fixed incentives. Another aspect to consider is the degree of control that the contractor has over the role that they are assigned. If a role requires interactions with other participants in order to be successful but the responsibility only resides with one of them, the responsible party is burdened with risk that they are not in a position to manage. In addition to being at the mercy of the other participant's good will, all factors affecting the transaction costs of interacting with these parties can also become contributors to risk, i.e. **Processes and Procedures**, **Organizational Structure** and **Systems and Procedures**.

One final aspect of risk to consider is when it is applied as a means to motivate. Avoidance of risk can be a powerful incentive for improving quality and performance. When risk is shared by a group of participants it can motivate them to improve the efficiency of their interactions and to work together towards a common goal. In a process such as **Requirements Engineering** which needs a high degree of efficient interaction to be successful, giving participants a stake in both the gains and the losses can act as a powerful motivation for cooperation.

3.3.3. Process Improvement Methodology

This exhaustive correlation between the component elements and attributes of both the Demand and Supply side **Contextual Artifacts** and the **Requisite**

Abilities represents a roadmap for process optimization. It is a holistic approach which ensures that all factors defining the **Requisite Abilities** *required* by a process are recognized; and furthermore presents all avenues available to the project manager that can be utilized to ensure that this requirement is fulfilled. Based on this analysis we can conclude that a **Systems Approach to Process Improvements** would consist of the following steps:

- **STEP 1**: Define the *Primary Purpose* of a particular project Process in the context of the **Need**
- **STEP 2**: Scrutinize the **Need** and **Environment** to determine which **Requisite Abilities** are needed to support *all* the functionalities of the **Process**
- **STEP 3**: For each **Requisite Ability** define the required
  - *Enabling Capacities*
  - *Performance*
  - *Limitations*
- **STEP 4**: Identify which **Project Organization** and **Agreement** elements can be utilized to provide the demanded *Enabling Capacities*
- **STEP 5**: Determine the specific configurations of these elements that will best fulfill the required *Performance* attributes while staying within the constraints of the *Limitations*.

Figure 25: Systems Approach to Process Improvement

4. Project Failure Modes

Having developed a systems approach to process improvements the question arises of whether it can be utilized as a means to mitigate project failure. However, before doing so we must first investigate the failure modes that exist on projects.

One may be tempted to think of project failures only in terms of disastrous events which end projects. However, while such events are known to occur every now and then, in many cases failures are not nearly as dramatic. Certainly, if we were to look at the other end of the spectrum, success can never be considered an absolute achievement. There is always room for improvement in the prosecution of the work and whether the final product is deemed to be successful or not depends upon the preferences and expectations of its client. For example a high quality, high cost product might be viewed as a success by a quality conscious client but a failure by a cost conscious one. In other words success is literally in the eye of the beholder.

It would therefore be more apt to think of a project as a multi-objective optimization effort wherein success is gauged by its ability to both deliver a product that is as satisfactory to its stakeholders as possible, and is also done so as efficiently as possible. Ergo, failures would be construed as unfulfilled requirements or inefficiencies in the prosecution of the work; for example mistakes that could have been avoided, or opportunities for efficiencies that were squandered.

We can therefore summarize that there are two basic failure modes for a project:

- **Product Failure**: Where the resulting product fails to satisfactorily fulfill the project's requirement set.
- **Process Failure**: Where the prosecution of the work exhibits inefficiencies resulting in wastage of time and resources.

However, if there is one thing that the modeling process has illustrated, it is the high degree of interaction between the elements of the **Project System**. So while we may be able to conceptually differentiate between the two forms of failure, in an actual project both go hand in hand.

This can be better understood if we assume for a moment that there could be such a thing as a project that is unconstrained by limitations on time or resources; a project where process efficiencies are not a concern. Such a project would theoretically never succumb to product failure as all requirements would ultimately be fulfilled to perfect satisfaction. Similarly a project which had no firm requirements whatsoever would always stay within budget and time constraints.

4.1. Product Failure Mitigation

For many projects, arriving at the state of concept/scope finalization can be a difficult and time consuming process. These are the projects in which at the outset, there is no clear understanding of what the final product will be like; often exacerbated by not having a clear understanding of what the requirements are, or whether or not they are even realistic.

Product Failure is defined as the inability of a product to fulfill its requirement set satisfactorily. One possible cause of this might be that the expectations are just too high, and simply cannot be fulfilled given the contextual constraints on the project. Alternatively, the expectations may be reasonable but the process for developing a solution concept that matches the requirement set is deficient.

In either case, what is needed to address these issues is an efficient **Requirements Engineering** process; one that would be able to promptly identify the requirements that must be changed or removed; and one that could also efficiently yield a solution for the set of requirements that *are* established, with a high degree of satisfaction.

This is of course in line with the failure mitigation approach identified in the thesis objectives. By improving the efficiency of the **Requirements Engineering** process we mitigate the chances of **Product Failure** occurrence.

4.1.1. Implications of Product Failure on Process Failure

Obviously improving the **Requirements Engineering** *process* has implications for mitigating **Process Failure** as well. As has already been alluded to before, even though conceptually Process and Product Failure have been differentiated, this does not mean that they are mutually exclusive in occurrence.

A simple way of looking at this is to observe that since the only things that project funds are ever expended on are the three basic resources: **Materials**, **Equipment/Facilities** and **Personnel**. Any performance improvement within the project system can be expected to have a process failure mitigation effect as well; **Requirements Engineering** process improvements being no exception. However, there can also be more profound impacts on process efficiencies depending on how quickly the finalization of product definition can be achieved.

To understand this lets begin by noting that while process failure is a concern throughout the period of performance, the potential for product failure is only limited to the time it takes to finalize the product definition. It should be clarified, however, that it is possible to have a project in which product development is not part of the scope, and consequently product failure is not a concern in such projects at all. A simple example would be that of a product assembly project in which the design and methodology are predefined and the only thing one has to worry about is managing the resources for execution. In such a case, execution would consist entirely of an implementation phase.

Alternatively, if we take the example of a new product prototype development project, **Requirements Engineering** continues through out the period of performance including any implementation of formal structure. So by the time an understanding of the final product is established, the project is practically at an end.

With these two examples representing the most extreme cases; for projects in general, the required level of **Requirements Engineering** can vary dramatically, and consequently the finalization of product definition can potentially be at any point during the course of a project.

Now as far as improving the **Requirements Engineering** process is concerned, the variance in product conceptualization requirements is immaterial; because a systemic approach to strengthening the system should be effective in improving the product's degree of requirements fulfillment (i.e. mitigation of product failure) in all cases – assuming of course that there is some product development included in the scope of work.

However, if a strengthened **Requirements Engineering** can also achieve the result of a final product definition faster, then it can have considerable ramifications for overall process efficiency as well. This is partly because of the effect that having a clear understanding of the scope of work can have on the ability to manage the usage of resources efficiently. Additionally it reduces the risk of rework in the event that a design refinement can render implemented work useless.

When the required scope of work is clear, seeking efficiencies (or mitigating process failures) becomes a function of the quality of your resources and systems, and your ability to manage your resources and systems. The fact that you are proceeding towards the fulfillment of an established scope of work, allows you to generate meaningful estimates of the projects demands, and to define a plan to work against; thereby enabling you to strive towards improving operational efficiencies and mitigating losses.

Conversely, during the conceptualizing phase, the fact that both the requirement set and the solution space are in flux till it ends, means that there can be no clear definition of what is being attempted until it is achieved. Consequently the operational requirements to sustain this effort cannot be estimated or planned for as effectively as they would be for a known scope of work; thus inflating the risks of process failure during this phase. By accelerating the finalization of the solution concept not only is the impact of this phase limited, but all subsequent work can be executed with higher efficiencies and lower risks.

Of course, as has been iterated repeatedly, every project is unique and therefore the actual proportion of work that is defined, and that which requires refinement, will vary vastly from project to project. However from a systemic perspective it is clear that improving the efficiency of the **Requirements Engineering** process can be a very viable mitigation strategy for both product and process failure.

4.1.2. Requirements Engineering

In order to identify the systemic factors that influence the efficiency of **Requirements Engineering** it is important to understand it first. To do so we will rely on a framework developed as part of the MIT-MASDAR Research Initiative program.

It should be recalled that the definition of **Project Executing** is the translation of a requirement set into a viable solution. As previously cited examples have illustrated, there can be a great deal of variability in the proportion and the overlap of **Requirements Engineering** and **Implementing** within the **Project Executing** phase. Depending on the project, **Requirements Engineering** could very well encompass **Designing** and **Implementing -** assuming of course that they are also part of the scope of work. From the perspective of this thesis, however, the exact moment at which **Requirements Engineering** ends is irrelevant. The real concern is identifying the factors that might delay the achievement of this goal within our generic project system.

The reason why this is such a matter of concern is that process efficiencies can be vastly improved with greater definition of the scope of work. This is why accelerating the establishment of the work definition and the management of changes is a primary concern in any project.

4.1.2.1. MIT-MASDAR Requirements Engineering Framework

This framework defines **Requirements Engineering** as a continuous staged process of design evolution, ultimately leading to a degree of product and scope clarity that can be accepted as a solution to the need(s) defined in the requirement set.

Each stage in this evolutionary process is referred to as a Design Iteration (D_n). A key concept of this framework is that the solution is *only* relevant in the context of the requirement that it fulfils. Therefore each Design Iteration is a representation of the current level of understanding of *both* the requirements and the solution space.

D*esign* = *f* (**R***equirement set,* **S***olution space)*

$D_n = f\,(R_n\,,\,S_n)$

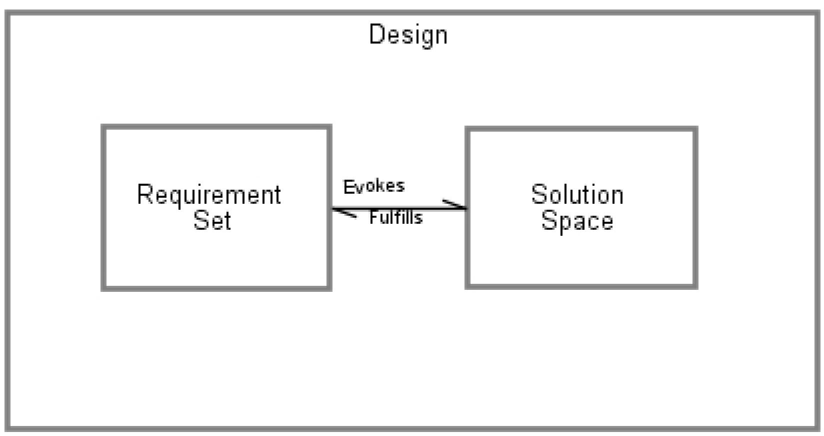

Figure 26: Design - Level 1

With every evolutionary step $D_0 \rightarrow D_n$ our understanding of both the problem and the solution is further refined, and the Design Iteration (D_{n+1}) produced as a result of an evolutionary step forms the basis of the following step in the evolution.

$D_n \rightarrow D_{n+1} \rightarrow D_{n+2}$

$R_n, S_n \rightarrow R_{n+1}, S_{n+1} \rightarrow R_{n+2}, S_{n+2}$

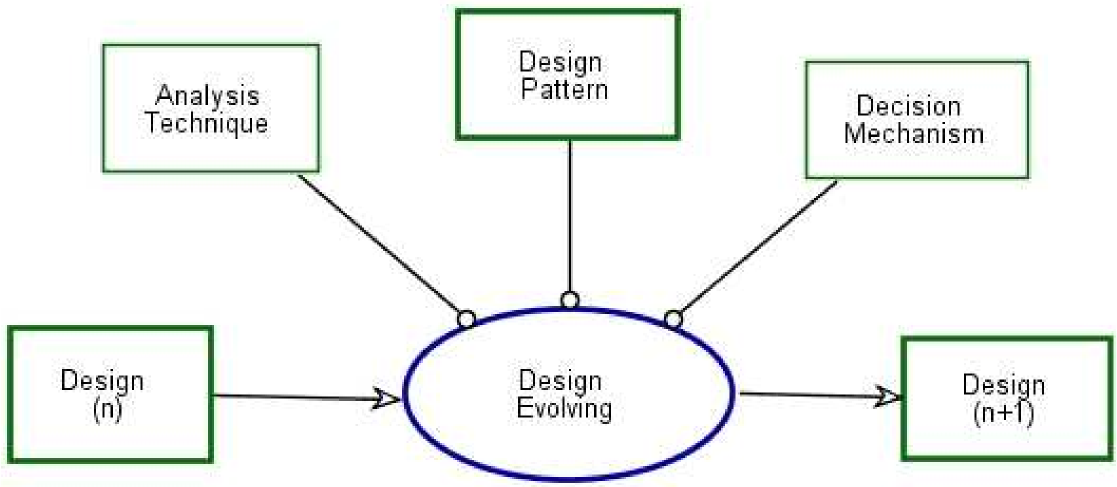

Figure 27: Design Evolving

From the project system perspective the project **Need** would be denoted as D_0 in this framework. The degree of detail and scope clarity that would be included in D_0 would define how much of a role **Requirements Engineering** would play in that particular project.

If we refer again to the product assembly example, it can be expected that in such a project both the **Requirement Set** and the **Solution Space** are already evolved to the point that implementation can proceed with out any further variations in the design. Consequently, **Requirement Engineering**'s role can be expected to be limited.

Alternatively the product prototype development example would most likely have a **Requirement Set** that is not fully developed and a large **Solution Space** that needs to be narrowed to a tangible, detailed and implementable form; guaranteeing that **Requirements Engineering** will dominate the **Project Executing** phase.

In general the more loosely defined the Requirement Set is, the wider the associated Solution Space will be, and the greater the need for Requirements Engineering will be. Then as the development proceeds, the Solution Space will begin to narrow and take form.

4.1.2.1.1. Requirement Set (R_n)

A **Requirement Set** is collection of information that must be taken into consideration at each step of the design refinement exercise. In addition to describing the desired functions, **Requirement Sets** also capture the context, constraints, performance expectations, solution preferences and solution process preferences. Specifically the following elements can be expected to exist in a requirements definition:

- Stakeholder(s)
- Value Added Operand(s)
- Required Function(s)
- Function attributes
    - Performance expectation
    - Relative importance
- Context
    - Elements (Objects)
    - Object Attributes
- Design Process Constraints / Preferences
    - Technical
    - Resource
    - Spatial
    - Interfacing
    - Regulatory
    - Methodology
- Solution Constraints /Preferences
    - Required Elements
    - Required Attributes
    - Relative importance

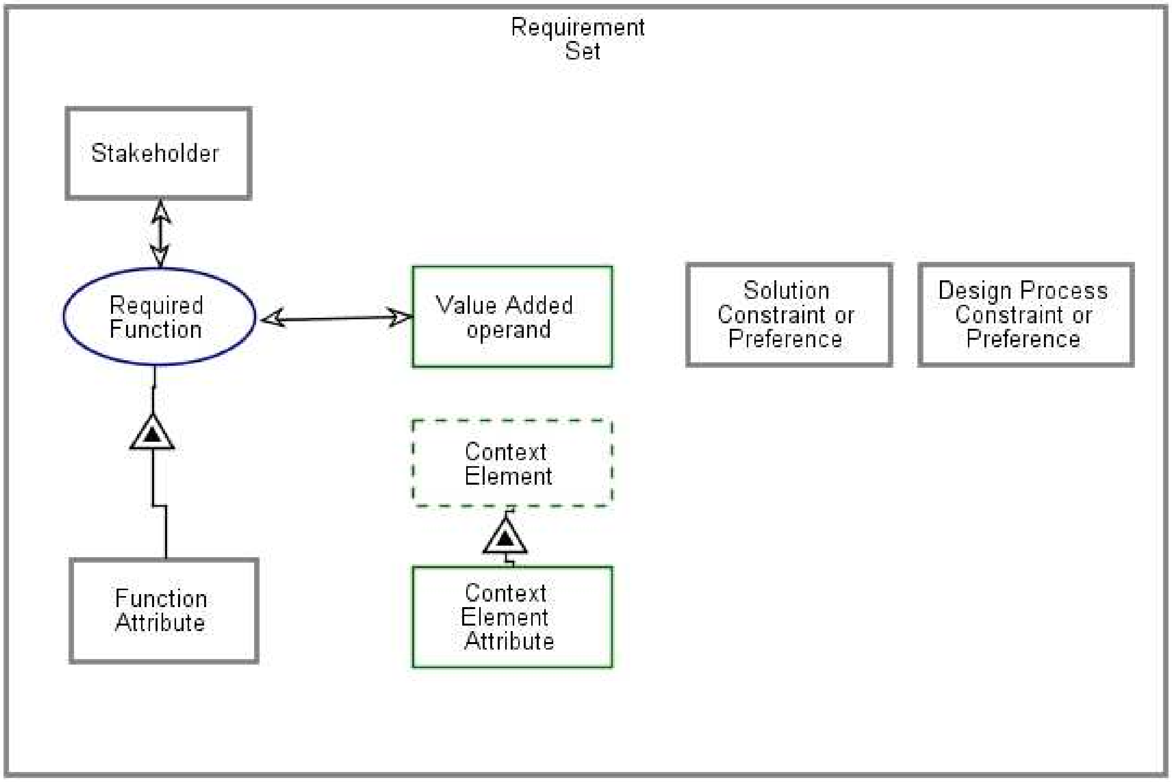

Figure 28: Requirements Set

4.1.2.1.2. Solution Space (S_n)

The solution portion of the design consists of a description of the solution system's:

- System Form
- Form attributes
- Operations
    - Value added Operation (fulfilling a need)
    - Supporting Operation (incidental/emergent)

- Operation Attributes
- Operands
  - o Value added Operation (fulfilling a need)
  - o Supporting Operation (incidental/emergent)

The more explicitly the form of the solution is defined, the narrower the remaining solution space will be. With each successive refinement step the solution is further constricted. It is up to the designer to decide at what point to stop the refinement process on the basis of having achieved a Requirement Set and Solution definition combination that are acceptable.

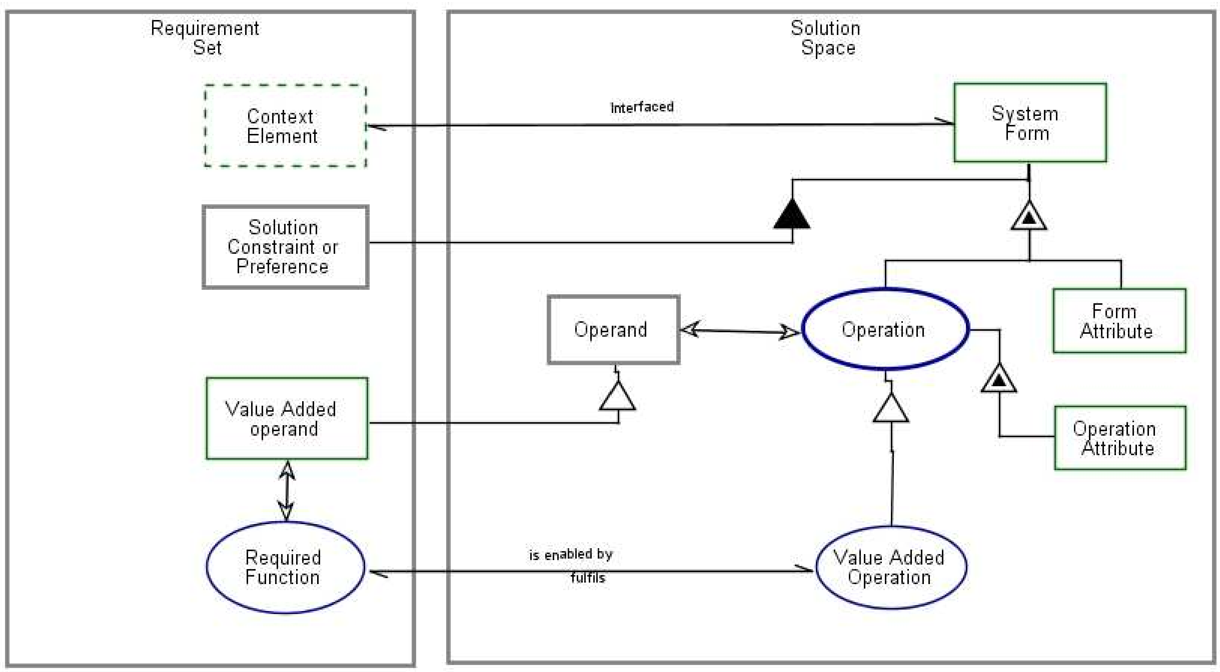

Figure 29: Solution Space

4.1.2.1.3. The Evolutionary Process

We now address the process that enables us to move from one level of evolution to the next.

$$D_n \rightarrow D_{n+1}$$

The purpose of each of these steps is to arrive at a more refined design and therefore to constrict the solution space. In order to do so we use the existing design definition (D_n) as a starting point to explore possible trajectories of design evolution. These trajectories are then analyzed and evaluated against the requirements. The process can be iterative and can result in a revaluation of the requirements as well. Ultimately, however, if the design development process is to progress, it must be converged to a more refined understanding of both the requirements and the solution space i.e. D_{n+1}

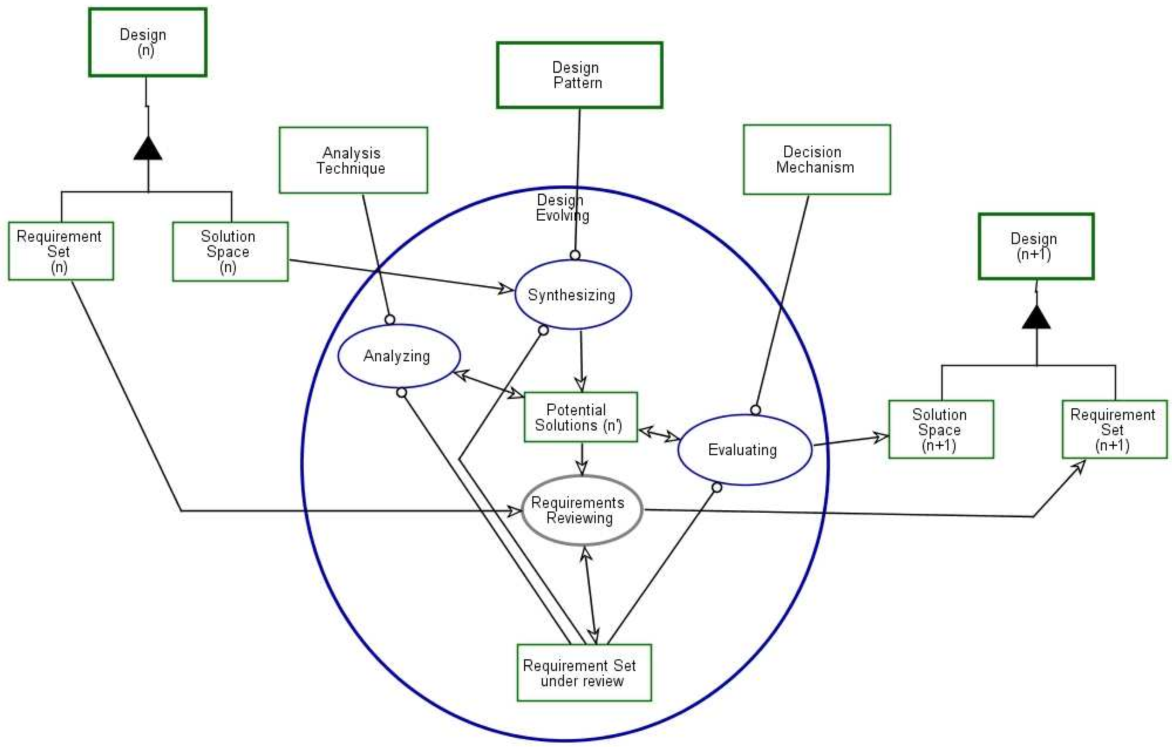

Figure 30: Design Evolving - Level 2

The four sub-steps of the evolutionary process discussed above are clarified below.

- **Synthesis:** The application of *design patterns* (discussed below) to explore possible trajectories within the solution space in directions that will improve the fulfillment of the existing requirements. During a single evolutionary step different patterns, or combinations of patterns, are applied to generate a range of potential solution trajectories (or refinements).
- **Analysis:** Analyzing the operations, performance and other attributes of the potential solution refinements.

- **Evaluation:** The potential solution refinements are compared against each other in terms of requirement fulfillment. This leads to the selection of the solution trajectory that best fulfills the existing/refined requirements.
- **Requirements review:** It is entirely possible that pursuing the above steps can result in the identification of shortcomings in the requirements.
    - ***Compromise -*** Some of the requirements could prove to be unrealistic or contradictory in the sense that a solution that fulfils all of them may not be possible. In such cases the requirements may have to be scaled back or preference weightings may have to be adjusted.
    - ***Completeness and Detailing -*** Alternatively, the exploration of certain trajectories may be impeded by the lack of certain required information. This could occur when a solution is detailed into specific subsystems and would lead to adding more details to the requirements
    - ***Discovery -*** Exploring various solution trajectories could result in the emergence of things that had not been previously considered. For example it might be realized that an important or desirable functionality was not originally included in the requirements and this may now be added.

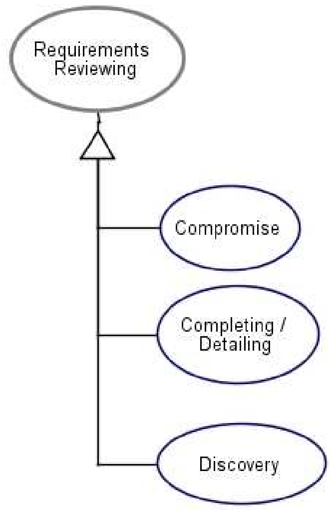

Figure 31: Requirements Reviewing

The cumulative effect of all these sub-steps is the concurrent refinement of both the requirements and the solution.

4.1.2.1.4. Design Patterns

A **Design Pattern** is a mode of thinking that enables synthesis. Every solution trajectory that is considered during synthesis follows a pattern of thought. In that sense these patterns are the building blocks of creativity.

The source of inspiration for these patterns can vary considerably. In some cases the requirements themselves may explicitly state the preferred design methodology. In other cases the preferences and the weighting of attributes within the requirements could implicitly govern the pattern(s) applied in the synthesis process. Looking outside of the requirements, the designer could literally draw on a life time of experiences to derive inspiration that is then applied as a pattern of thought in design development.

As the above discussion indicates, there could potentially be infinite applicable patterns for any given design problem. Nonetheless, following are some broad categories of patterns that are commonly applied.

- **Configurations**: These are preconceived patterns of form or the arrangement of form elements
- **Hierarchal Sequence**: Patterns which defines the strategy by which multiple subsystems within a larger multi-functional system are to be developed. Could be sequential, in parallel or iteratively.
- **Convergence**: The pre-defined existence (as a consequence of a preceding refinement effort) of certain elements may lead to interdependent design considerations
- **Technology / Resource driven**: Being constrained to use a specific technology or resource may affect and/or limit the possible solution trajectories
- **Codes / Regulation**: A requirement to adhere to certain codes or regulations can affect and/or limit the possible solution trajectories

- **Heuristics / Best Practice**: These can be individual, organizational or school-of-thought approaches adopted by a designer to address a particular type of problem.
- **Tradeoffs**: This can be described as the hierarchy amongst attributes

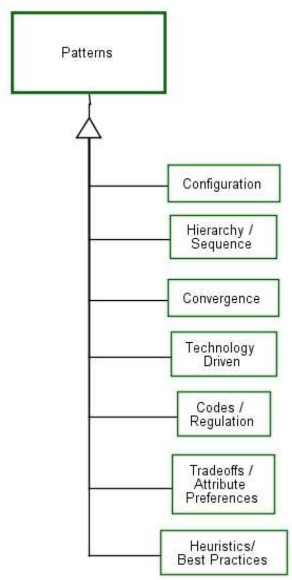

Figure 32: Design Patterns

4.1.2.1.5. Analysis Techniques

Analysis Technique is a general term that refers to any methodology that is used to gauge the performance or value of a potential solution. This is a necessary first step towards the ultimate goal on deciding upon a single solution trajectory to carry forward as the result of the current design refinement cycle.

Possible analysis techniques that could be applied include:

- Mathematical calculations
- Computer simulations
- Numerical analysis
- Standardized rating scale
- Failure testing

It is not necessary for all of these evaluations to be discrete. A subjective or heuristic based rating system could also be applied here. However, the distinct feature of all of these analysis mechanisms is that the solution system is gauged on its own merits rather than on a relative basis to other possible solution systems.

The selection of the appropriate analysis methodology would also depend upon whether the design concept is defined conceptually or has physical form

4.1.2.1.6. Evaluation Mechanisms

An **Evaluation Mechanism** is a methodology for selecting the optimal solution trajectory from *amongst* the potential solution. Unlike the analysis techniques which focus on analyzing the properties of each solution system independently, the **Evaluation Mechanisms** are aimed at comparative analysis amongst the range of solution systems. This step does of course utilize the information gathered during the analysis phase to conduct the comparative analysis amongst the contenders and choose the best option to move forward.

4.1.3. Requirements Engineering Process – Key Observations

To summarize the analysis of the **Requirements Engineering** process, the following are some key observations:

- **Requirements Engineering** is foremost a knowledge management effort
- It requires the absorption of various types of requirements information from derived from stakeholders and the context
- These requirements are constantly under review in the light of possible solutions.
- The design evolution process requires the application of design methodologies (or patterns) for synthesizing solution trajectories
- It requires the application of analysis and evaluation methodologies to decide which direction to allow the solution to evolve.

From these observations we can infer that:

- The availability of relevant information, as and when required can be expected to be a critical factor in the efficient running of the process

- The sources of these inputs may be a wide range of stakeholders; each of whom may be unique in terms of their expertise, perspectives, vested interests, availability, commitment to the project etc.
- It may not be sufficient for the stakeholders to simply provide their input, but in fact the design evolution may depend upon human-to-human interactions of these stakeholders.
- There may be contextual barriers that hinder the ability to facilitate the required interactions amongst these stakeholders
- It is likely that the information in question will not always be categorized as data. An idea or an opinion are examples of information forms that tend to be subjective and cannot be standardized, thus making them less pre-disposed to technology enabled data management
- Some design flaws may not become evident until a the product can be given physical form
- The greater the initial ambiguity regarding the final product the greater the risk of product failure
- The greater the inherent complexity of the project, the greater the risk of product failure

4.1.4. Requirements Engineering Process Improvement

Improving the process of **Requirements Engineering** would elicit the following benefits:

- Mitigation of the Product Failures for the project as a whole
- Mitigation of Process Failures associated with this process
- Mitigation of Process Failures during Designing and Implementing assuming that product concept finalization can be accelerated

Following is the application of the **Systems Approach to Process Improvements** on the **Requirements Engineering** process.

STEP 1: Define the *Primary Purpose* of a particular project Process in the context of the **Need**

The primary purpose of the **Requirements Engineering** process is design generation and refinement. At the very least this requires the availability of relevant expertise and the ability to manage the design related information as it goes through the process of evolution.

STEP 2: Scrutinize the **Need** and **Environment** to determine which **Requisite Abilities** are needed to support *all* the functionalities of the **Process**

Capacity/ Capability to work equates to the ability to develop a design and manage knowledge

Ability to Communicate and **Ability to Make Decisions** are relevant because most **Requirements Engineering** efforts entail the involvement of numerous stakeholders who must be able to interact effectively and work collaboratively to evolve the design.

Ability to Monitor relates to being able to assess the progress in design evolution, the performance of the participants, and the utilization of resources.

Ability to Incentivize Work is relevant whenever a process involves an agent. However, this is a particularly important factor in **Requirements Engineering** because of the potential involvement of a wide range of stakeholders with varying inputs and level of commitment to the process.

STEP 3: For each **Requisite Ability** define the required

- *Enabling Capacities*
- *Performance*
- *Limitations*

Based on our understanding of the **Requirements Engineering** process itself we can define the expected *Enabling Capacities* as follows:

- **Capacity and Capability**
    - Availability of required expertise, knowledge and relevant design patterns
    - Authorization for stakeholders to be involved in the process
    - Information processing and storage enablers
    - Design Generation enablers
    - Procedures for Synthesis, Analysis and Evaluation
    - Experience of the stakeholders in collaborative efforts
- **Ability to Incentivize Work**

    - Incentives to be involved in the process
    - Incentives to collaborate with one another
    - Incentives to adhere to the information exchange and maintenance protocols
    - Incentives for Reporting Progress and Resource Utilization Status
    - Incentives for Performance
- **Ability to Communicate**
    - Formal information transfer enablers
    - Informal information transfer enablers
    - Information sharing protocols
    - Willingness to communicate
- **Ability to Monitor Status**
    - Progress Reporting Enablers
    - Resource Utilization Tracking Enablers
    - Information sharing protocols
    - Willingness to allow monitoring
- **Ability to Make Decisions**
    - Authority Hierarchies
    - Decision Making and Dispute Resolution protocols
    - Willingness to cooperate

Since this is a generalized example we are not in a position to define the *Performance* or *Limitations* specifically. However, we are able to correlate the factors with the **Need** and **Environment** that would determine the required *Performance* or which might place Supply side *Limitations.* To avoid redundancy this correlation has been merged in to the STEP 4 output.

STEP 4: Identify which **Project Organization** and **Agreement** elements can be utilized to provide the demanded *Enabling Capacities*

The following mapping depicts in **red** how the **Requisite Abilities** *Enabling Capacities* identified in STEP 3 are impacted by the demand side determinants of *Performance* and *Limitations*

It also includes in **green** those elements within the **Project Organization** and **Agreements** that can supply the necessary *Enabling Capacities.*

- **Capacity and Capability**
  - *Availability of required expertise, knowledge and design patterns*
    - ↔ Need - Scope size
    - ↔ Need - Degree of evolution
    - ↔ Need - Novelty of the work
    - ↔ Need - Funding Limits
    - ↔ Need - Expected period of performance
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations
    - ↔ Environment - Resource Availability
    - ↔ Environment - Funding Availability
    - ↔ Environment - Work Availability
    - ↔ Personnel (Experience, Training, Quantity)
    - ↔ Incentives
  - *Authorization for stakeholders to be involved in the process*
    - ↔ Environment - Regulations and Legal considerations
    - ↔ RE Methodology (Principle participants list)
    - ↔ Assignment of a role in the RE process
  - *Information processing and storage enablers*
    - ↔ Need - Scope size
    - ↔ Need - Novelty of the work
    - ↔ Need - Number of External Stakeholders

- ↔ Need - Funding Limits
- ↔ Environment - Physical Site Conditions
- ↔ Environment - Regulations and Legal considerations
- ↔ Environment - Resource Availability
- ↔ Environment - Funding Availability
- ↔ Personnel (Training, Quantity)
- ↔ Equipment/Facility (Quality, Ease of Use, Suitability and Capacity)

- *Design Generation enablers*
  - ↔ Need - Scope size
  - ↔ Need - Degree of evolution
  - ↔ Need - Novelty of the work
  - ↔ Need - Funding Limits
  - ↔ Environment - Physical Site Conditions
  - ↔ Environment - Resource Availability
  - ↔ Environment - Funding Availability
  - ↔ Environment - Competitive Environment
  - ↔ Environment - Work Availability
  - ↔ Personnel (Experience, Training, Quantity)
  - ↔ Equipment/Facility (Quality, Ease of Use, Suitability and Capacity)
- *Procedures for Synthesis, Analysis and Evaluation*
  - ↔ Need - Scope size
  - ↔ Need - Degree of evolution
  - ↔ Need - Novelty of the work
  - ↔ RE Methodology (Design strategy)
- *Experience of the stakeholders in collaborative efforts*
  - ↔ Need - Novelty of the work
  - ↔ Environment - Physical Site Conditions
  - ↔ Environment - Resource Availability
  - ↔ Environment - Funding Availability
  - ↔ Environment - Competitive Environment
  - ↔ Environment - Work Availability
  - ↔ Personnel (Experience)

- **Ability to Incentivize Work**
  - *Incentives to be involved in the process*
    - ↔ Need - Scope size
    - ↔ Need - Degree of evolution
    - ↔ Need - Novelty of the work
    - ↔ Need - Number of external stakeholders
    - ↔ Need - Funding Limits
    - ↔ Need - Expected period of performance
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations

- ↔ Environment - Resource Availability
- ↔ Environment - Funding Availability
- ↔ Environment - Competitive Environment
- ↔ Environment - Work Availability
- ↔ Assignment of Role or Responsibility
- ↔ Incentives / Allocation of Risk

o *Incentives to collaborate with one another*

- ↔ Need - Scope size
- ↔ Need - Degree of evolution
- ↔ Need - Degree of modularity
- ↔ Need - Novelty of the work
- ↔ Need - Number of external stakeholders
- ↔ Need - Funding Limits
- ↔ Need - Expected period of performance
- ↔ Environment - Physical Site Conditions
- ↔ Environment - Regulations and Legal considerations
- ↔ Environment - Resource Availability
- ↔ Environment - Funding Availability
- ↔ Environment - Competitive Environment
- ↔ Environment - Work Availability
- ↔ Assignment of Responsibility
- ↔ Incentives / Allocation of Risk

o *Incentives to adhere to the information exchange and maintenance protocols*

- ↔ Need - Scope size
- ↔ Need - Funding Limits
- ↔ Need - Expected period of performance
- ↔ Environment - Physical Site Conditions
- ↔ Environment - Regulations and Legal considerations
- ↔ Environment - Resource Availability
- ↔ Environment - Funding Availability
- ↔ Environment - Competitive Environment
- ↔ Environment - Work Availability
- ↔ Assignment of Role or Responsibility
- ↔ Incentives / Allocation of Risk

o *Incentives for Reporting Progress and Resource Utilization Status*

- ↔ Need - Scope size
- ↔ Need - Funding Limits
- ↔ Need - Expected period of performance
- ↔ Environment - Physical Site Conditions
- ↔ Environment - Regulations and Legal considerations
- ↔ Environment - Resource Availability
- ↔ Environment - Funding Availability
- ↔ Environment - Competitive Environment
- ↔ Environment - Work Availability
- ↔ Assignment of Role or Responsibility

    - ↔ Incentives / Allocation of Risk
  - *Incentives for performance*
    - ↔ Need - Scope size
    - ↔ Need - Degree of evolution
    - ↔ Need - Degree of modularity
    - ↔ Need - Novelty of the work
    - ↔ Need - Number of external stakeholders
    - ↔ Need - Funding Limits
    - ↔ Need - Expected period of performance
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations
    - ↔ Environment - Resource Availability
    - ↔ Environment - Funding Availability
    - ↔ Environment - Competitive Environment
    - ↔ Environment - Work Availability
    - ↔ Incentives / Allocation of Risk

- **Ability to Communicate**
  - *Formal information transfer enablers*
    - ↔ Need - Scope size
    - ↔ Need - Degree of modularity
    - ↔ Need - Number of external stakeholders
    - ↔ Need - Funding Limits
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations
    - ↔ Environment - Resource Availability
    - ↔ Environment - Funding Availability
    - ↔ Environment - Competitive Environment
    - ↔ Personnel (Training, Quantity)
    - ↔ Equipment/Facility (Quality, Ease of Use, Suitability and Capacity)
    - ↔ Assignment of Role or Responsibility
  - *Informal information transfer enablers*
    - ↔ Need - Scope size
    - ↔ Need - Degree of modularity
    - ↔ Need - Number of external stakeholders
    - ↔ Need - Funding Limits
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations
    - ↔ Environment - Resource Availability
    - ↔ Environment - Funding Availability
    - ↔ Environment - Competitive Environment
    - ↔ Personnel (Experience, Quantity)
    - ↔ Equipment/Facility (Quality, Ease of Use, Suitability and Capacity)

- ↔ Assignment of Role or Responsibility
- o *Information sharing protocols*
  - ↔ Need - Scope size
  - ↔ Need - Degree of modularity
  - ↔ Need - Number of external stakeholders
  - ↔ Environment - Physical Site Conditions
  - ↔ Environment - Regulations and Legal considerations
  - ↔ Environment - Competitive Environment
  - ↔ RE Methodology (Information Sharing Protocols)
  - ↔ Organizational Structure (Communications Hierarchy)
  - ↔ Agreements - Processes and Procedures
- o *Willingness to communicate*
  - ↔ Environment - Physical Site Conditions
  - ↔ Environment - Regulations and Legal considerations
  - ↔ Environment - Resource Availability
  - ↔ Environment - Funding Availability
  - ↔ Environment - Competitive Environment
  - ↔ Personnel (Experience, Quantity)
  - ↔ Incentives / Allocation of Risk

- **Ability to Monitor Status**
  - o *Progress Reporting Enablers*
    - ↔ Need - Scope size
    - ↔ Need - Funding Limits
    - ↔ Need – Number of External Stakeholders
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations
    - ↔ Environment - Resource Availability
    - ↔ Environment - Funding Availability
    - ↔ Personnel (Training, Quantity)
    - ↔ Equipment/Facility (Quality, Ease of Use, Suitability and Capacity)
    - ↔ Assignment of Role or Responsibility
  - o *Resource Utilization Tracking Enablers*
    - ↔ Need - Scope size
    - ↔ Need - Funding Limits
    - ↔ Need - Number of External Stakeholders
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations
    - ↔ Environment - Resource Availability
    - ↔ Environment - Funding Availability
    - ↔ Environment - Work Availability
    - ↔ Personnel (Training, Quantity)
    - ↔ Equipment/Facility (Quality, Ease of Use, Suitability and Capacity)

- ↔ Assignment of Role or Responsibility
- *Information sharing protocols*
  - ↔ Need - Scope size
  - ↔ Need - Degree of modularity
  - ↔ Need - Number of external stakeholders
  - ↔ Environment - Physical Site Conditions
  - ↔ Environment - Regulations and Legal considerations
  - ↔ Environment - Competitive Environment
  - ↔ RE Methodology (Information Sharing Protocols)
  - ↔ Organizational Structure (Communications Hierarchy)
  - ↔ Agreements - Processes and Procedures
- *Willingness to allow monitoring*
  - ↔ Environment - Physical Site Conditions
  - ↔ Environment - Regulations and Legal considerations
  - ↔ Environment - Resource Availability
  - ↔ Environment - Funding Availability
  - ↔ Environment - Competitive Environment
  - ↔ Personnel (Experience, Quantity)
  - ↔ Incentives / Allocation of Risk

- **Ability to Make Decisions**
  - *Authority Hierarchies*
    - ↔ Need - Scope size
    - ↔ Need - Degree of evolution
    - ↔ Need - Degree of modularity
    - ↔ Need - Novelty of the work
    - ↔ Need - Number of external stakeholders
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations
    - ↔ Environment - Competitive Environment
    - ↔ RE Methodology (Design strategy)
    - ↔ Assignment of authority to make decisions
    - ↔ Organizational Structure (Communications Hierarchy)
    - ↔ Agreements - Processes and Procedures
  - *Decision Making and Dispute Resolution protocols*
    - ↔ Need - Scope size
    - ↔ Need - Degree of evolution
    - ↔ Need - Degree of modularity
    - ↔ Need - Novelty of the work
    - ↔ Need - Number of external stakeholders
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations
    - ↔ Environment - Competitive Environment
    - ↔ RE Methodology (Decision Making protocols)
    - ↔ Agreements - Processes and Procedures

- *Willingness to cooperate*
  - ↔ Environment - Physical Site Conditions
  - ↔ Environment - Regulations and Legal considerations
  - ↔ Environment - Resource Availability
  - ↔ Environment - Funding Availability
  - ↔ Environment - Competitive Environment
  - ↔ Personnel (Experience, Quantity)
  - ↔ Incentives / Allocation of Risk

STEP 5: Determine the specific configurations of these elements that will best fulfill the required *Performance* attributes while staying within the constraints of the *Limitations*.

Since this is a generalized approach, specific configurations are precluded. However, the mapping in STEP 4 provides the full range of Demand and Supply side factors that would need to be taken into consideration in order to develop a specific configuration that caters to the complete set of **Requisite Abilities** needed by a particular process.

4.1.5. Process Improvement Conclusions

This analysis illustrates quite profoundly the fact that multiple elements within the **Project System** can influence a single area of interest. This is true for both sides of the equation: the Demand side and the Supply side. Understanding these multifaceted relationships significantly improves our ability to mould the project system in such a way that it elicits the type of performance that is being sought.

On the Demand side it prevents us from making the mistake of not recognizing the full range of factors that can dictate the required level of performance and the overarching constraints on the system. On the Supply side it offers the range of ways that this performance can be achieved while staying within the constraints. These managing approaches can then be applied in a complementary fashion or, in the event that one of the Supply side elements is already constrained to a configuration that is not conducive to the goals, there is the potential for balancing out these negative effects by working with other Supply side elements that are exhibiting flexibility.

4.2. Systems Approach to Information Flow Management

Applying the **Systems Approach to Process Improvements** on the **Requirements Engineering** process was beneficial in more ways than one. The fact that improvements in this system have the potential for mitigating Product Failure occurrence is obviously the first; and was in fact the reason why the process improvement methodology was applied to it in the first place.

However, it is also important to note that **Requirements Engineering** represents what is probably the most interaction intensive process that exists on a project. Accordingly, stakeholder interactions and knowledge management were among the objectives that were considered when the **Requisite Abilities** for this process were being defined in the preceding analysis. The outcome of this was, that in addition to addressing the factors related with design generation, the analysis results also illustrated which factors needed to be considered to bolster what are critical components of information flow management i.e. knowledge management and stakeholder interactions

The reason why this is significant is that earlier in the thesis, information flow was identified as a systemic factor that impacts the overall performance of a **Project System**, as well its ability to rapidly identify an issues that may occur.

Extracting the relevant elements from within the previous analysis we are left with the following mapping that pertains specifically to information flow enabling abilities:

- **Capacity and Capability**
  - *Information processing and storage enablers*
    - ↔ Need - Scope size
    - ↔ Need - Degree of modularity
    - ↔ Need - Novelty of the work
    - ↔ Need - Number of External Stakeholders
    - ↔ Need - Funding Limits
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations
    - ↔ Environment - Resource Availability
    - ↔ Environment - Funding Availability
    - ↔ Personnel (Training, Quantity)
    - ↔ Equipment/Facility (Quality, Ease of Use, Suitability and Capacity)
  - *Experience of the stakeholders in collaborative efforts*
    - ↔ Need - Novelty of the work
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Resource Availability
    - ↔ Environment - Funding Availability
    - ↔ Environment - Competitive Environment
    - ↔ Environment - Work Availability
    - ↔ Personnel (Experience)

- **Ability to Incentivize Work**
    - *Incentives to collaborate with one another*
        - ↔ Need - Scope size
        - ↔ Need - Degree of evolution
        - ↔ Need - Degree of modularity
        - ↔ Need - Novelty of the work
        - ↔ Need - Number of external stakeholders
        - ↔ Need - Funding Limits
        - ↔ Need - Expected period of performance
        - ↔ Environment - Physical Site Conditions
        - ↔ Environment - Regulations and Legal considerations
        - ↔ Environment - Resource Availability
        - ↔ Environment - Funding Availability
        - ↔ Environment - Competitive Environment
        - ↔ Environment - Work Availability
        - ↔ Assignment of Responsibility
        - ↔ Incentives / Allocation of Risk
    - *Incentives to adhere to the information exchange and maintenance protocols*
        - ↔ Need - Scope size
        - ↔ Need - Funding Limits
        - ↔ Need - Expected period of performance
        - ↔ Environment - Physical Site Conditions
        - ↔ Environment - Regulations and Legal considerations
        - ↔ Environment - Resource Availability
        - ↔ Environment - Funding Availability
        - ↔ Environment - Competitive Environment
        - ↔ Environment - Work Availability
        - ↔ Assignment of Role or Responsibility
        - ↔ Incentives / Allocation of Risk
    - *Incentives for Reporting Progress and Resource Utilization Status*
        - ↔ Need - Scope size
        - ↔ Need - Funding Limits
        - ↔ Need - Expected period of performance
        - ↔ Environment - Physical Site Conditions
        - ↔ Environment - Regulations and Legal considerations
        - ↔ Environment - Resource Availability
        - ↔ Environment - Funding Availability
        - ↔ Environment - Competitive Environment
        - ↔ Environment - Work Availability
        - ↔ Assignment of Role or Responsibility
        - ↔ Incentives / Allocation of Risk

- **Ability to Communicate**
    - *Formal information transfer enablers*

- ↔ Need - Scope size
- ↔ Need - Degree of modularity
- ↔ Need - Number of external stakeholders
- ↔ Need - Funding Limits
- ↔ Environment - Physical Site Conditions
- ↔ Environment - Regulations and Legal considerations
- ↔ Environment - Resource Availability
- ↔ Environment - Funding Availability
- ↔ Environment - Competitive Environment
- ↔ Personnel (Training, Quantity)
- ↔ Equipment/Facility (Quality, Ease of Use, Suitability and Capacity)
- ↔ Assignment of Role or Responsibility

- *Informal information transfer enablers*
  - ↔ Need - Scope size
  - ↔ Need - Degree of modularity
  - ↔ Need - Number of external stakeholders
  - ↔ Need - Funding Limits
  - ↔ Environment - Physical Site Conditions
  - ↔ Environment - Regulations and Legal considerations
  - ↔ Environment - Resource Availability
  - ↔ Environment - Funding Availability
  - ↔ Environment - Competitive Environment
  - ↔ Personnel (Experience, Quantity)
  - ↔ Equipment/Facility (Quality, Ease of Use, Suitability and Capacity)
  - ↔ Assignment of Role or Responsibility
- *Information sharing protocols*
  - ↔ Need - Scope size
  - ↔ Need - Degree of modularity
  - ↔ Need - Number of external stakeholders
  - ↔ Environment - Physical Site Conditions
  - ↔ Environment - Regulations and Legal considerations
  - ↔ Environment - Competitive Environment
  - ↔ Instrument System (Information Sharing Protocols)
  - ↔ Organizational Structure (Communications Hierarchy)
  - ↔ Agreements - Processes and Procedures
- *Willingness to communicate*
  - ↔ Environment - Physical Site Conditions
  - ↔ Environment - Regulations and Legal considerations
  - ↔ Environment - Resource Availability
  - ↔ Environment - Funding Availability
  - ↔ Environment - Competitive Environment
  - ↔ Personnel (Experience, Quantity)
  - ↔ Incentives / Allocation of Risk

- **Ability to Monitor Status**
  - *Progress Reporting Enablers*
    - ↔ Need - Scope size
    - ↔ Need - Funding Limits
    - ↔ Need - Number of External Stakeholders
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations
    - ↔ Environment - Resource Availability
    - ↔ Environment - Funding Availability
    - ↔ Personnel (Training, Quantity)
    - ↔ Equipment/Facility (Quality, Ease of Use, Suitability and Capacity)
    - ↔ Assignment of Role or Responsibility
  - *Resource Utilization Tracking Enablers*
    - ↔ Need - Scope size
    - ↔ Need - Funding Limits
    - ↔ Need - Number of External Stakeholders
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations
    - ↔ Environment - Resource Availability
    - ↔ Environment - Funding Availability
    - ↔ Environment - Work Availability
    - ↔ Personnel (Training, Quantity)
    - ↔ Equipment/Facility (Quality, Ease of Use, Suitability and Capacity)
    - ↔ Assignment of Role or Responsibility
  - *Information sharing protocols*
    - ↔ Need - Scope size
    - ↔ Need - Degree of modularity
    - ↔ Need - Number of external stakeholders
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations
    - ↔ Environment - Competitive Environment
    - ↔ Instrument System (Information Sharing Protocols)
    - ↔ Organizational Structure (Communications Hierarchy)
    - ↔ Agreements - Processes and Procedures
  - *Willingness to allow monitoring*
    - ↔ Environment - Physical Site Conditions
    - ↔ Environment - Regulations and Legal considerations
    - ↔ Environment - Resource Availability
    - ↔ Environment - Funding Availability
    - ↔ Environment - Competitive Environment
    - ↔ Personnel (Experience, Quantity)
    - ↔ Incentives / Allocation of Risk

- **Ability to Make Decisions**
    - *Authority Hierarchies*
        - ↔ Need - Scope size
        - ↔ Need - Degree of evolution
        - ↔ Need - Degree of modularity
        - ↔ Need - Novelty of the work
        - ↔ Need - Number of external stakeholders
        - ↔ Environment - Physical Site Conditions
        - ↔ Environment - Regulations and Legal considerations
        - ↔ Environment - Competitive Environment
        - ↔ Instrument System (Communications partners)
        - ↔ Assignment of authority to make decisions
        - ↔ Organizational Structure (Communications Hierarchy)
        - ↔ Agreements - Processes and Procedures
    - *Decision Making and Dispute Resolution protocols*
        - ↔ Need - Scope size
        - ↔ Need - Degree of evolution
        - ↔ Need - Degree of modularity
        - ↔ Need - Novelty of the work
        - ↔ Need - Number of external stakeholders
        - ↔ Environment - Physical Site Conditions
        - ↔ Environment - Regulations and Legal considerations
        - ↔ Environment - Competitive Environment
        - ↔ Instrument System (Decision Making protocols)
        - ↔ Agreements - Processes and Procedures
    - *Willingness to cooperate*
        - ↔ Environment - Physical Site Conditions
        - ↔ Environment - Regulations and Legal considerations
        - ↔ Environment - Resource Availability
        - ↔ Environment - Funding Availability
        - ↔ Environment - Competitive Environment
        - ↔ Personnel (Experience, Quantity)
        - ↔ Incentives / Allocation of Risk

The resulting mapping of elements and abilities represents a framework for addressing the strengthening of the communications and monitoring abilities of any process within the **Project System**. Rather, it is a framework that *should* be applied to every process within the system, if information asymmetry is to be reduced, and overall information flows are to be improved.

In my experience it is common for projects to view managing communications and monitoring as simply a matter of assigning responsibility for them to a particular functional group. On a construction project for example there is typically a collection of personnel with titles such as project engineers, quantity surveyors, quality officers, safety officers and contract administrators. These personnel act as liaisons between the field and the project managing team for a range of information including progress status, resource utilization, work quality, safe practice adherence and change management.

What is extraordinary is how common it is to simply hire the people with appropriate titles and then leave it to them to figure out how they are going to fulfill their responsibilities. Countless successfully completed projects are testament to the fact that somehow these individuals do manage to achieve their purpose. However, the battles that rage between the “field” and “the bean counters” on most projects are equally telling of the difficulties faced in this sink-or-swim approach to information management; not to mention the risks of failures that this approach posses to a project.

The findings of the **Systems Approach to Process Improvements** suggest that it would be far more efficient to expend some effort on *enabling* the various processes themselves to facilitate the transfer of relevant information. In other words, rather than hoping that the information liaison officers will figure out a way to achieve this critical role, each process should be scrutinized at the outset from the perspective of its informational inputs and outputs and through a combination of tools, incentives and allocations of responsibility, the necessary information flows should be facilitated. Certain personnel may still be needed to act as information liaisons, however, instead of having to beg or badger people for what they need they could rely on a system that is designed for this purpose.

In essence this would be a process of improving the integration of the Project Wide **Communication System** with the communication and monitoring protocols that exist within every **Instrument System**. Bear in mind that even without giving these aspects of an **Instrument System** due attention, eventually the information liaisons and the process agents do manage to establish some form of informal protocols; otherwise **Executing Status** would simply cease to flow. The point however, is that using this informal approach entails significant performance and failure risks that could potentially be mitigated through a systems approach that focuses on ensuring that communication enablers are present at both the project wide and the process level.

4.3. Systems Approach to Organizational Structure

It was mentioned earlier during a discussion of **Organizational Structures** that in some schools of thought Inter-firm and Intra-firm project structures are considered to be alternative methodologies[7].

[7] Carroll, Glenn. Teece, David. “Firms Markets and Hierarchies”. Oxford University Press. (1999)

In the light of our enhanced understanding of factors related with information flow it would be worthwhile at this stage to revisit the distinctions between these two forms of organizational governance.

If we consider the typical hierarchal functional-department approach to **Organizational Structure**, the basic criticism against it is that it constrains information flow to vertical channels.

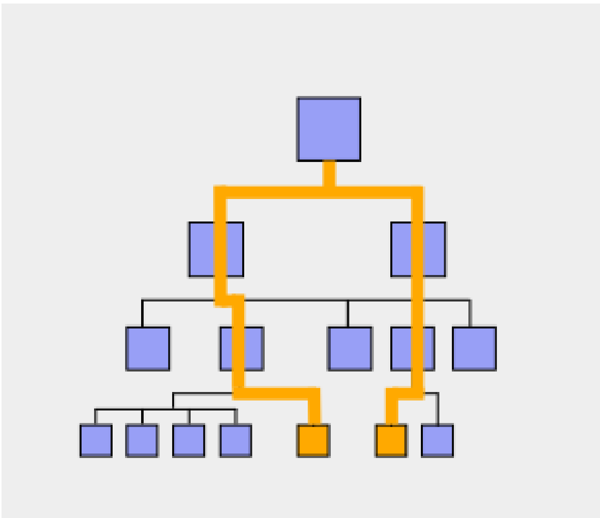

Figure 33: Typical Organizational Structure Hierarchy

Needless to say this is not conducive for activities that require a high degree of interaction between members from different functional departments. Within a single firm a common approach to addressing this issue is to transition from a **Departmental Organization** [*which closely maps to the structure of the supporting* *technologies*] to a **Project Team Organization** [*which groups experts from the various disciplines together into a single team all reporting to a common authority*][8].

It is evident that the basic principle behind this strategy is one of reducing transaction cost. It is based on the premise that the interactions between individuals in a single department will be more efficient than if those same individuals are segregated amongst different departments. Being part of a single organizational unit has the effect of simplifying the processes and procedures that its members use to interact with one another. Adjustments to the allocation of roles and responsibilities are quicker and can be optimized more easily. Reporting to a common authority makes the alignment of incentives and the sharing of risk far easier as well.

The question arises of why all this can be achieved with relative ease in a single firm but is more difficult when dealing with independent organizations. The simple reason is that transaction costs within a firm are limited to begin with, and risks that pertain to a firm as a whole, are already distributed fairly uniformly amongst all of its employees. Finally, a major component of the incentives (i.e. monetary) is already guaranteed for all the firm members in the form of a salary.

Independent firms on the other hand are legal entities between whom the risk allocation is far more discrete. Furthermore, the formalized agreements (contracts) that connect them, constrain the **Processes and Procedures** through which they can interact; and any variation in the roles that they espouse entails the question of whether they are being adequately incentivized or not.

[8] Allen, Thomas. Henn, Gunter. "The Organization and Architecture of Innovation". Elsevier Inc. (2007)

The take away from this is not that single firm and multi-firm interactions are fundamentally different. Rather it is the realization that even though the complexity varies between inter-firm and intra-firm interactions, the factors that govern these interactions are the same, and the ultimate objective remains the same: To develop efficient and multimodal means of interaction between the participants:

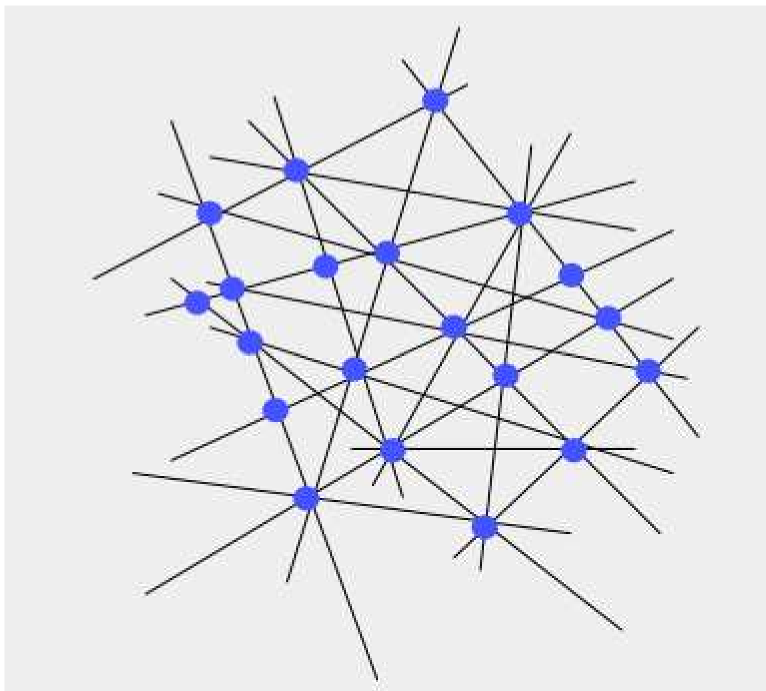

Figure 34: Organizational Network

Efficiency of interactions is achieved by mitigating the associated transaction costs through collective management of the personnel, equipment, facilities, organizational structure, processes and procedures, roles and responsibilities, incentives and risk allocations.

Not only will successful alignment of these factors complement the overall objective; they can also be used to balance the effect of those which might be constrained to a deficient configuration. This latter ability being enhanced by correlating all the **Contextual Artifact** elements to a common set of interaction and performance attributes i.e. the **Requisite Abilities**.

4.4. Process Failure Mitigation

Process failure is described as a waste of resources and time during the course of managing and executing the project. At the end of the day this is basically what every project wants to avoid to the greatest extent possible.

4.4.1. Manifestations of Process Failures

There are basically three ways in which Process Failures manifest themselves:

- **Errors –**Execution mistakes or quality deficiencies manifesting themselves as events; that need to be rectified through the application of additional effort and resources.
- **Inefficiencies –** Excessive utilization of resources in an ongoing operation, that could be mitigated through process improvements
- **Product–** Additional work due to a Product Failure. Unlike error where an execution mistake required rectification, in this case the quality of the

previously executed work is not in question but the work itself has become obsolete.

Each of these manifestations has underlying causes of its own.

Process Failure Manifestations	Underlying Causes
Errors	Agent, Instrument or Instrument System Error
	Interaction Error
Inefficiency	Agent, Instrument or Instrument System Inefficiency
	Interaction Inefficiency
	Exogenous Change in Conditions
Product	Requirements Engineering Failure
	Exogenous Change in Requirements

Table 1: Process Failure Manifestations

4.4.1.1. Agent, Instrument or Instrument System Failures

Agents, Instruments and Instrument Systems can contribute to failures in the form of Errors as well as Inefficiencies. In the case of Errors it generates Rework which is defined as remedial actions that must be taken to undo the erroneous work and to implement the work properly. This relegates as waste, any time and resources that were previously expended in implementing the inadequate (failed) design, as well as any that are spent on undoing it.

In the case of Inefficiencies there is no requirement for Rework as the waste is experienced in the form of excessive use of time and resources for work that in terms of quality is acceptable.

In either case, however, the failure manifests itself specifically in the execution of the process that these implementers have been assigned to work on.

4.4.1.2. Interaction Failures

Interaction failures may be better understood as failures of communication. These can also manifest themselves as both Errors and Inefficiencies. An example of an Interaction Error would be a communication breakdown where the participant tasked with an implementation task receives faulty instructions. The resulting work would still be classified as an error but the underlying cause would not be deficiencies of any of the implementers.

An example of Interaction Inefficiency could be any activity that requires participants to interact but is associated with high transaction costs. Ultimately any transaction costs that could have been avoided will equate to a waste of time and resources i.e. Process Failure.

4.4.1.3. Product Failures

Product Failures also result in the generation of Rework. In this case, however, the work that has to be rectified is not deficient in terms of execution quality, but in its fulfillment of the **Requirement Set**.

4.4.1.4. Exogenous Effects

Exogenous events are happenings that are outside the control of the **Project System**. They may or may not be foreseen but they cannot be prevented from occurring in any case. They can manifest themselves as changes in conditions, changes in requirements, or, in extreme cases, reduction/destruction of work done. Examples would include inclement weather, strikes, resource scarcity, and changes in scope.

- The impact of a change in conditions would generally be felt on process efficiencies. However, depending on the change this could be a positive or negative effect.
- Similarly there can be positive and negative changes in requirements as well. However, the danger entailed in new requirements is that they can potentially render existing design work obsolete (retroactive product failure), which might in turn generate rework. Any additional work added

as a consequence of a new requirement would not be construed as a waste. However, dealing with an unexpected change requires additional iterations of the **Requirements Engineering** process. Since these are unplanned events they can be particularly prone to Interaction Errors and Inefficiencies. Moreover the amount of effort expended in this iteration can depend upon the existing level of information asymmetry. Therefore any extra effort expended in contending with information asymmetry reflects a waste.

- If an event causes work done to be destroyed it will either generate rework or result in extreme cases result in work stoppage.

4.4.2. Process Failure Mitigation

All of our conclusions thus far lead us to affirm that mitigation of process failure is only achievable via process improvements. The effectiveness of this strategy, however, can depend significantly on how it is applied. If one relies on the "manage the problem/ fire fighting" approach they are predestined to reactively chasing one weakest link after the other until the project is completed. Equally misguided is the belief that simply allocating all project processes to various functional agents will enable their successful execution.

A **Systems Approach to Process Improvements**, however, is what this thesis argues constitutes the most viable strategy to process failure mitigation. Wherein each process is enabled from the outset by a set of managing elements that are designed on the basis of fulfilling *all* of the **Requisite Abilities** needed for that process to function:

- The capability and capacity needed to execute the work
- The ability to seek and receive necessary instructions
- Sufficient incentives to motivate the responsible agents to pursue the work according to expectations
- Sufficient empowerment of these agents to make the necessary decisions that the work might entail
- The ability to report status so as to enable progress and performance assurance and problem detection

Not only would such an approach mitigate failures and improve performance at the individual process level; it would have a collective impact on improving systems integration throughout the project. It would reduce transaction costs and informational asymmetry and thereby increase the performance of the **Project System** as whole, and its ability to address problems when they arise.

5. Project Information Dynamics Model

One of the conclusions of this thesis is that information flow plays a critical role in the over all efficiency of a project. This chapter relates to the development if a System Dynamics model to simulate this effect.

5.1. Basic Assumptions

The context specific nature of project artifacts precludes the generation of meaningful mathematical relationships between artifact elements and the impact that they would have on information flow. However, what can be modeled is how project performance might vary between a scenario where information flow is instantaneous and perfect, and one which reflects information asymmetry.

Specifically the impact of information flow on four processes has been modeled.

- **Resource Replenishment –** Reflects the process by which the gap between **Available Resources** and **Required Resources** is determined and then used as a basis for hiring additional resources. This is an **Enabling** function.
- **Resource Utilization –** Reflects the efficiency of **Available Resource** utilization. This may manifest itself in any function of the process.
- **Rework Discovery –** Reflects the rate at which errors are discovered which moves previously completed work back into the **Work to Do** stock. This is an **Assessing** function.
- **Exogenous Change in Requirements –** Reflects how the amount of work added in the event of an exogenous change in requirements would be affected

by the information flow. This is part of the **Requirements Engineering** process.

The information related variables that have been included are:

- Information Quality
- Information Delay

With respect to the information flow factors that have been discussed earlier, the **Information Flow Quality** variable reflects the collective impact of **Bandwidth** limitations and the **Noise** factor. While the **Information Flow Delay** variable exclusively reflects the **Delay** factor.

The model that was developed for the thesis is actually an evolved form of a Project Execution System Model that was developed by Dr. James Lyneis. In its original form the model did not incorporate information flow factors explicitly; and of the four processes listed above only **Rework Discovery** was included.

Therefore the first step was to incorporate these processes into the basic model.

5.2. Incorporation of Project Processes into the Model

5.2.1. Resource Replenishment

To include Resource Replenishment into the model it was necessary to first incorporate the concept of Intra-phase dynamics. Although not included in the model originally the incorporation of this dynamic was also based on methodologies developed by Dr. Lyneis. The purpose of this change was to build in the concept that a project consists of a sequence of tasks which have must be addressed according to precedence rather then a set of independent unrelated ones. This implies that at the start of the project the **Total Work Available to do** is not the same as the **Total Work to Do**. Rather the **Total Work Available to Do** is defined as a function of **Work Believed to be Completed** and **Total Work to Do.** The greater the **Work Believed to be Completed,** the greater the portion of **Total Work to Do** that becomes available to be executed.

As a result of this change, since the **Total Work Available to Do** is constantly varying the **Required Resources** are varying as well. However, whether or not the project is able to address all of the **Total Work Available to Do** depends upon **Available Resources** being sufficient. The **Available Resources** are defined as a stock which has inflows (**Resource Adding**) and outflows (**Resource Shedding**) of resources based on the perceived need.

One of the factors that impacts **Available Resources** is a **Resource Mobilization Plan**. This was generated by simulating the model with no **Exogenous Changes**, infinite **Available Resources**, perfect **Execution Quality,** perfect **Resource Utilization**, perfect **Information Flow Quality** and zero **Information Flow Delay.** In such a scenario the only factors affecting the project were the **Total Work Available to do** dynamic and the resource **Productivity**. The resulting **Required Resources** distribution was therefore reflected the project's resource needs in the most optimal conditions. This best case scenario distribution was then adopted as the **Resource Mobilization Plan.**

Another factor that is important in this dynamic is the **Known Gap in Resource Fulfillment.** This is defined as the gap between **Available Resources** and **Required Resources,** however it is delayed representation of this calculation. The delay is equivalent to the **Information Flow Delay** defined for the project.

Forecasted Resource Requirements is implemented so as to follow the **Resource Mobilization Plan** as long as the **Known Gap in Resource Fulfillment** is found to be negative, i.e. **Available Resources** exceed **Required Resources.** This is a safe strategy that maximizes the chances that resources will be available for the project even if they are not being utilized. However, if the **Known Gap in Resource Fulfillment** should become positive i.e. **Required Resources** exceed **Available Resources** then it sets the **Forecasted Resource Requirements** to be equivalent to the **Available Resources** plus **Known Gap in Resource Fulfillment**. However, given the delay intrinsic in **Known Gap in Resource Fulfillment** this forecast value is based on old resource status, i.e. it suffers from fixed duration information asymmetry.

The **Resource Adding** flow is defined to add resources as long as the demand is increasing but stops if the **Forecasted Resource Requirements** becomes equivalent to or less than the **Available Resources**.

The **Resource Shedding** flow will shed resources if **Forecasted Resource Requirements** becomes less than the **Available Resources**, however, it will only do so if there is a **Willingness to Shed Resources.** The **Willingness to Shed Resources** is a switch that becomes active after the project has achieved a **Fraction of Work Believed to be Complete** that exceeds 60%. This is to avoid resource shedding at an early stage in the project when there may be underutilized **Available Resources** but which are known to be needed in the near future when the **Total Work Available to do** will increase.

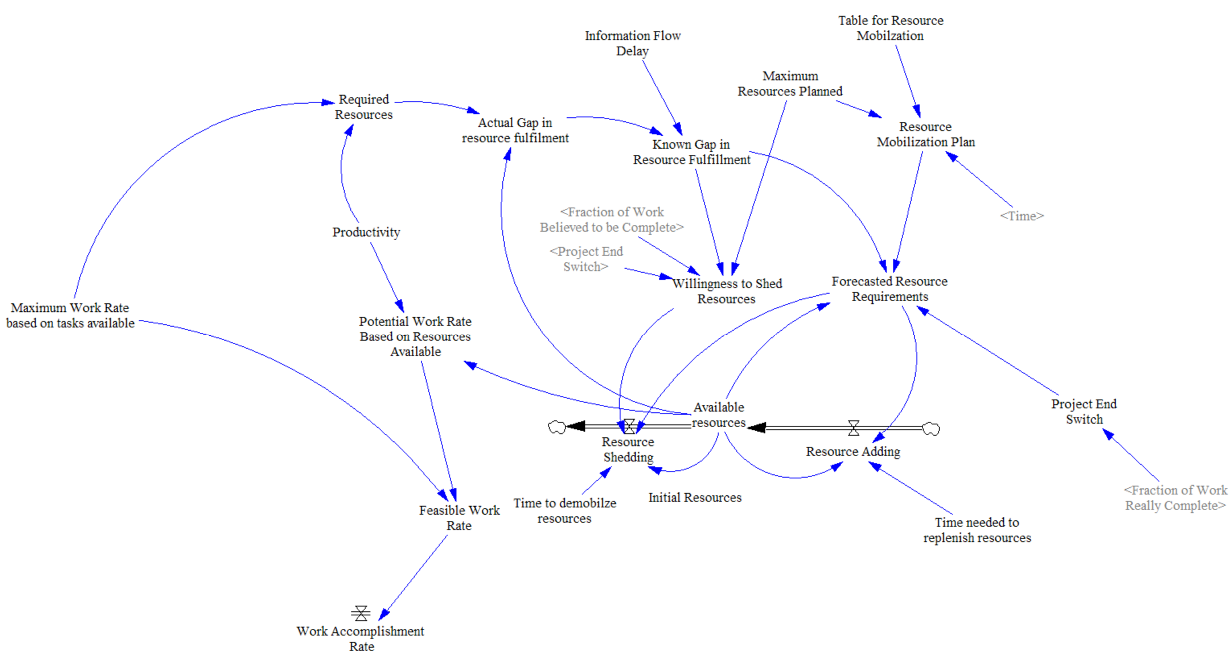

Figure 35: Resource Replenishment Dynamic

5.2.2. Exogenous Changes in Requirements

One of the impacts that an **Exogenous Change in Requirements** can generate is an increase in **Total Work to Do.**

- Partly to address the actual work that the change entails
- Partly in the effort to understand the change and determine its impact

The first of these two is not impacted by information flow factors. However it is affected by how much of the project work is already completed. This is because a greater amount of **Work Done** entails an increased likelihood that effort will have to be expended undoing work that has already been executed. Accordingly the **Effect of work progress on change impact** is utilized to increase the impact if more of the project is already complete. The result is that at an earlier stage in the project only a fraction of the **Maximum work added per change** would be actually added to the **Total Work to do.** However, towards the end of the project the entire value can be expected to be added.

For the second type of impact both the **Information Flow Delay** and the **Information Flow Quality** are factored as drivers for additional work in conjunction with the **Time needed to make a decision** and **Work Added per day of decision making.**

The occurrence of Exogenous Changes is generated by a **Random Number Generator**.

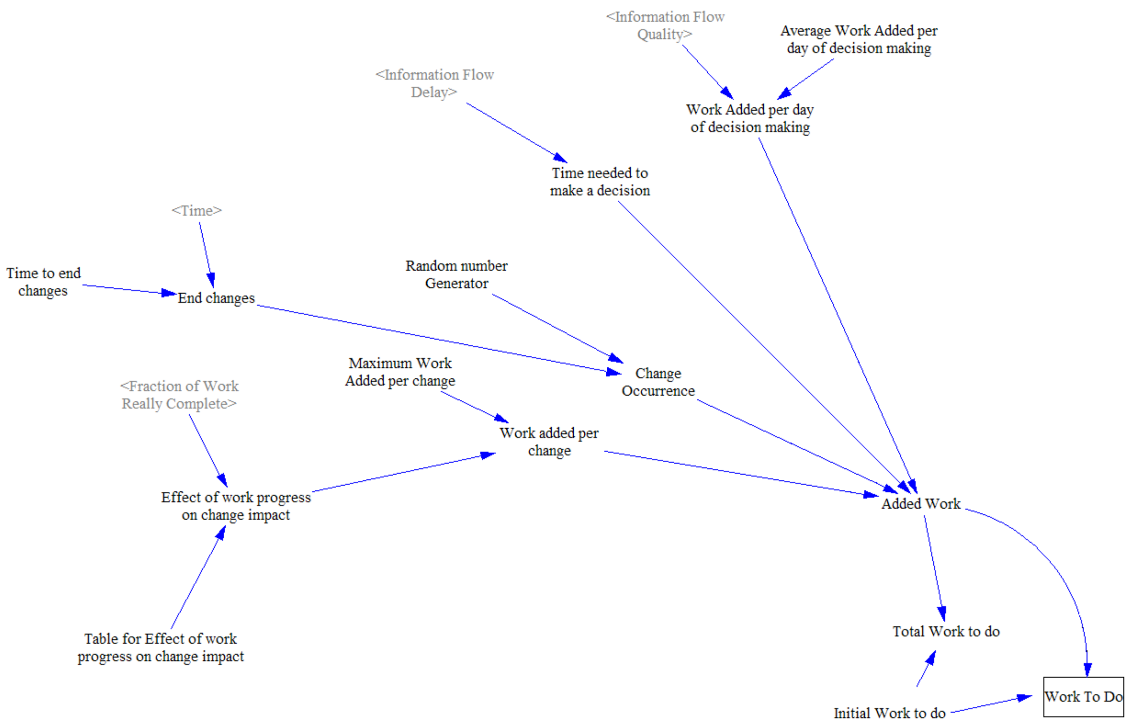

Figure 36: Exogenous Changes in Requirements Dynamic

5.2.3. Rework discovery time

Rework Discovery reflects a form of information asymmetry that was already present in the original model. However, it was not defined explicitly as being influenced by information flow factors. It did however, show **Fraction of Work Really Complete** as a factor affecting the time needed to discover rework; i.e. the greater the fraction completed the shorter the **Rework Discovery** time.

While maintaining the general principles of this approach, the only change made was to make the **Maximum time to discover rework** and the **Minimum time to discover rework** functions of the **Information Flow Delay.**

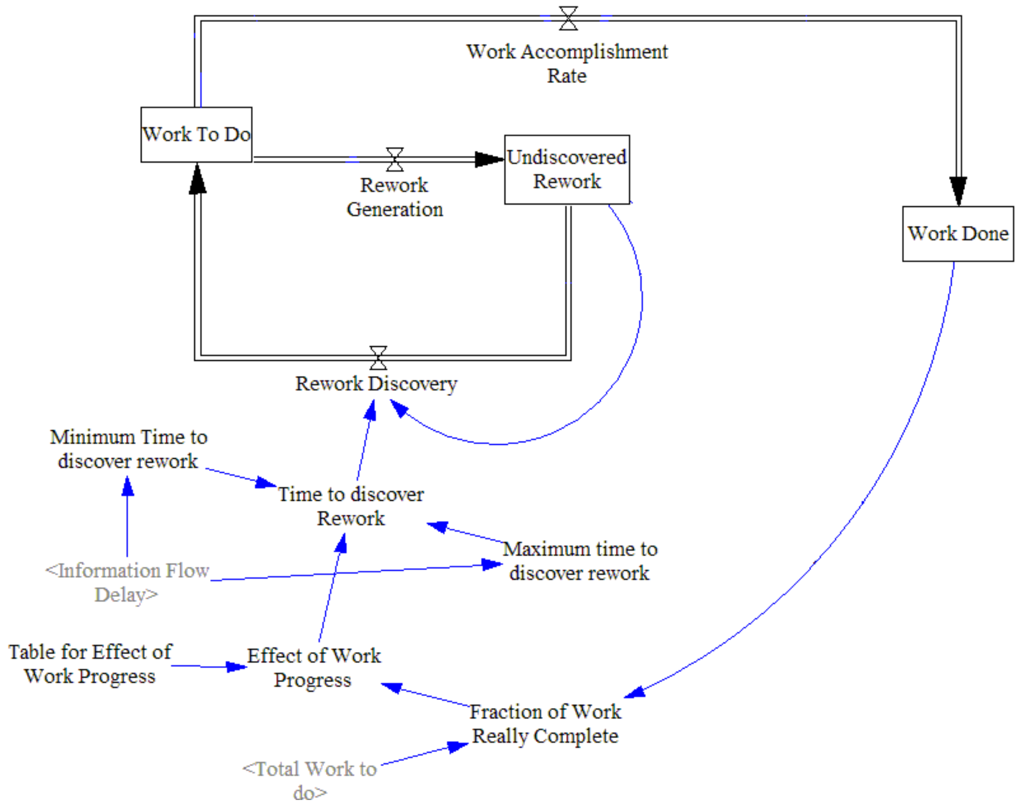

Figure 37: Rework Discovery Dynamic

5.2.4. Resource Utilization Efficiency

To incorporate the impact of inefficient utilization of **Available Resources,** a variable called **Resource Utilization Efficiency** has been incorporated into the model as a factor in the calculation of **Feasible Work Rate**. The **Resource Utilization Efficiency** factor itself is modeled as being impacted by **Information Flow Quality.**

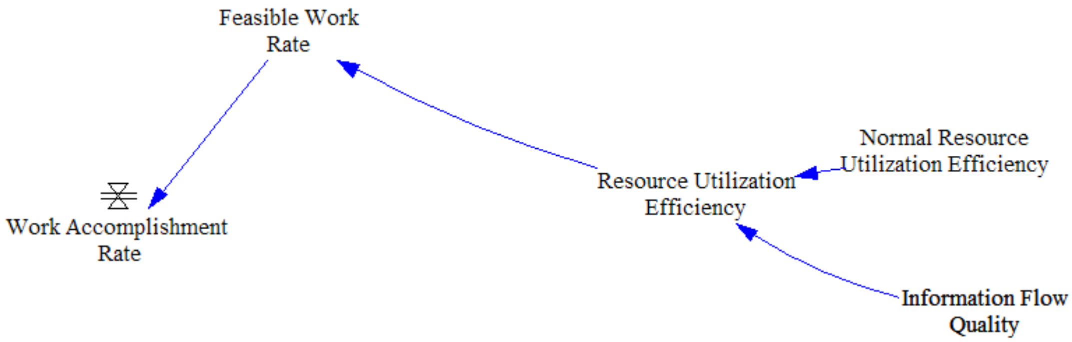

Figure 38: Resource Utilization Dynamic

5.3. Model Simulations

5.3.1. Thesis Run 1 – Baseline Simulation

This simulation assumed:

- Execution Quality = 100%
- Resource Utilization = 100%
- Information Flow Quality = 100%
- Information Flow Delay = 0 Days
- Exogenous Change Events = 0

It established the following optimal performance values:

- Total Duration = 160 days
- Cumulative Work Done = 100 Tasks
- Cumulative effort Expended = 5983 Resources

The purpose of this simulation was to establish a baseline from which variations could be measured.

	Execution Quality	Resource Utilization	Information Flow Quality	Information Flow Delay	Exogenous Changes	Total Duration	Cumulative Work Done	Cumulative Effort Expended	Duration % Change	Work Done % Change	Effort Expended % Change
Units	-	-	-	*Days*	*Events*	*Days*	*Tasks*	*Resources*	-	-	-
Thesis Run 1	100%	100%	100%	0	0	160	100	5983	0%	0%	0%

Table 2: Thesis Run 1 - Baseline Data

5.3.2. Thesis Run 8 –Information Factors Impact on Resource Replenishment and Utilization

This simulation assumed:

- Execution Quality = 100%
- Resource Utilization = 100%
- Information Flow Quality = 90%
- Information Flow Delay = 4 Days (2.5% of optimal Total Duration)
- Exogenous Change Events = 0

It established the impact of information factors on resource replenishment and utilization in perfect execution conditions, and with no change events:

- Total Duration = 166 days (+4%)
- Cumulative Work Done = 100 Tasks (0%)
- Cumulative effort Expended = 6662 Resources (+11%)

We can observe that even under perfect execution conditions, information factors can impact the project performance. In this case the impact is felt partially due to the inability of the project to react quickly enough in terms of resource loading, and also due to a reduction in the **Work Rate** due to **Information Flow Quality** impacts on **Resource Utilization**.

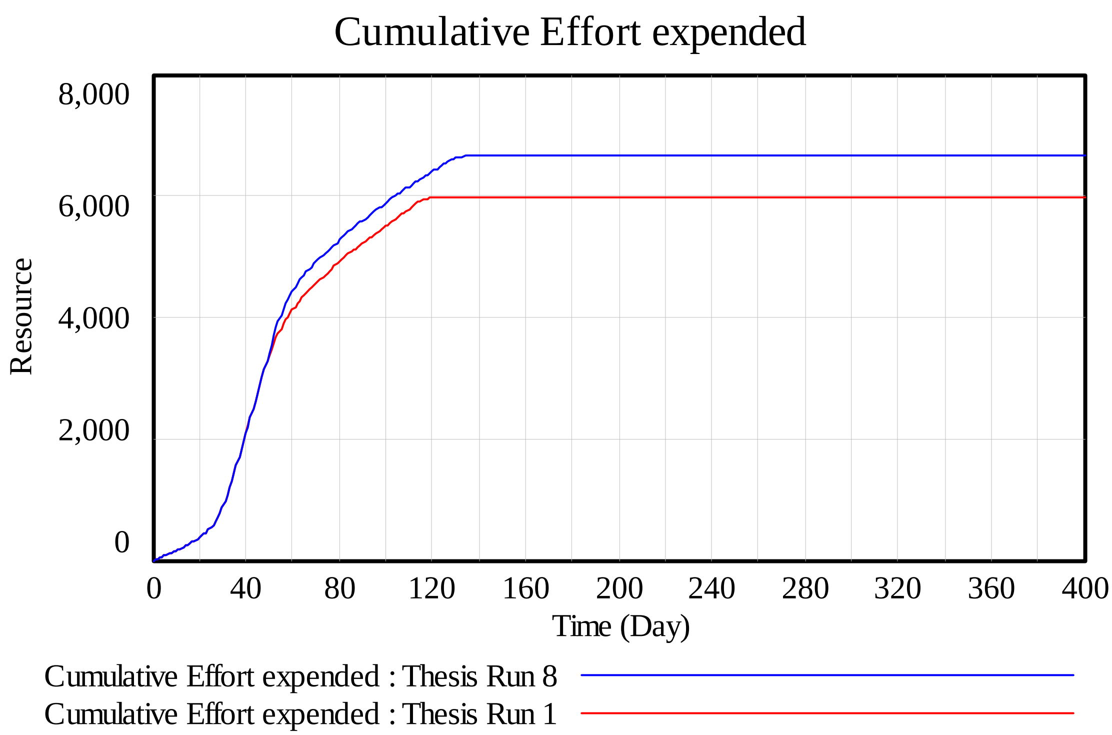

Figure 39: Cumulative Effort Expended Thesis Run 8 vs. Baseline

	Execution Quality	Resource Utilization	Information Flow Quality	Information Flow Delay	Exogenous Changes	Total Duration	Cumulative Work Done	Cumulative Effort Expended	Duration % Change	Work Done % Change	Effort Expended % Change
Units	-	-	-	*Days*	*Events*	*Days*	*Tasks*	*Resources*	-	-	-
Thesis Run 1	100%	100%	100%	0	0	160	100	5983.38	0%	0%	0%
Thesis Run 8	100%	100%	90%	4	0	166	100	6662	4%	0%	11%

Table 3: Thesis Run 8 vs. Baseline Data

5.3.3. Thesis Run 2 – Impact of Exogenous Changes

This simulation assumed:

- Execution Quality = 100%
- Resource Utilization = 100%
- Information Flow Quality = 100%
- Information Flow Delay = 0 Days
- Exogenous Change Events = 2

It established the impact of exogenous changes under perfect information and execution conditions:

- Total Duration = 168 days (+5%)
- Cumulative Work Done = 112 Tasks (+13%)
- Cumulative effort Expended = 6420 Resources (+7%)

The purpose of the simulation was to have the ability to account for change effects that are independent of information factors.

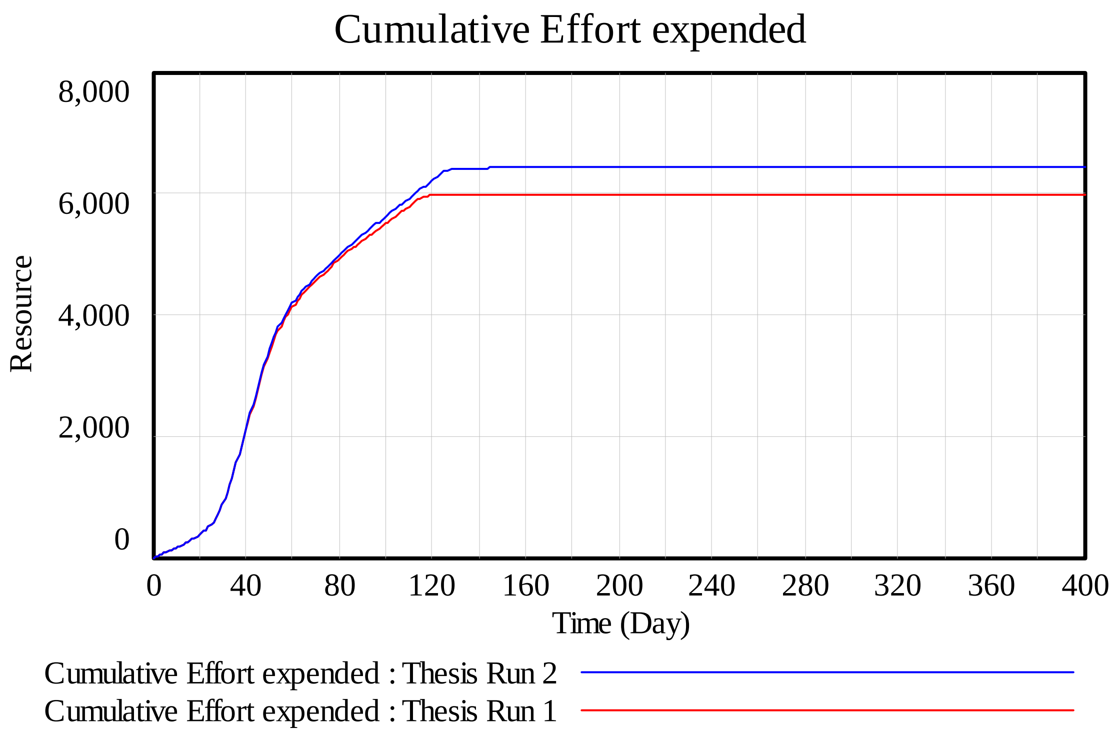

Figure 40: Cumulative Effort Expended Thesis Run 2 vs. Baseline

	Execution Quality	Resource Utilization	Information Flow Quality	Information Flow Delay	Exogenous Changes	Total Duration	Cumulative Work Done	Cumulative Effort Expended	Duration % Change	Work Done % Change	Effort Expended % Change
Units	-	-	-	*Days*	*Events*	*Days*	*Tasks*	*Resources*	-	-	-
Thesis Run 1	100%	100%	100%	0	0	160	100	5983	0%	0%	0%
Thesis Run 2	100%	100%	100%	0	2	168	112.656	6420	5%	13%	7%

Table 4: Thesis Run 2 vs. Baseline Data

5.3.4. Thesis Run 7 – Impact of Information factors in the presence of Exogenous Changes

This simulation assumed:

- Execution Quality = 100%
- Resource Utilization = 100%
- Information Flow Quality = 90%
- Information Flow Delay = 4 Days (2.5% of optimal Total Duration)
- Exogenous Change Events = 2

It established the impact of information factors in the presence of exogenous changes, but in the absence of any reduction in the **Execution Quality** or **Resource Utilization**.

- Total Duration = 189 days (+18%)
- Cumulative Work Done = 130 Tasks (+30%)
- Cumulative effort Expended = 7830 Resources (+31%)

Part of the impact observed can be attributed to impacts on resource replenishment and utilization. However, even if that impact is discounted we still note a significant increase in all factors. Particularly worth noting is the variation in **Cumulative Work Done,** which is not affected by resources. This factor went up from 13% to 30% purely as a consequence of information factors in conjunction with exogenous changes.

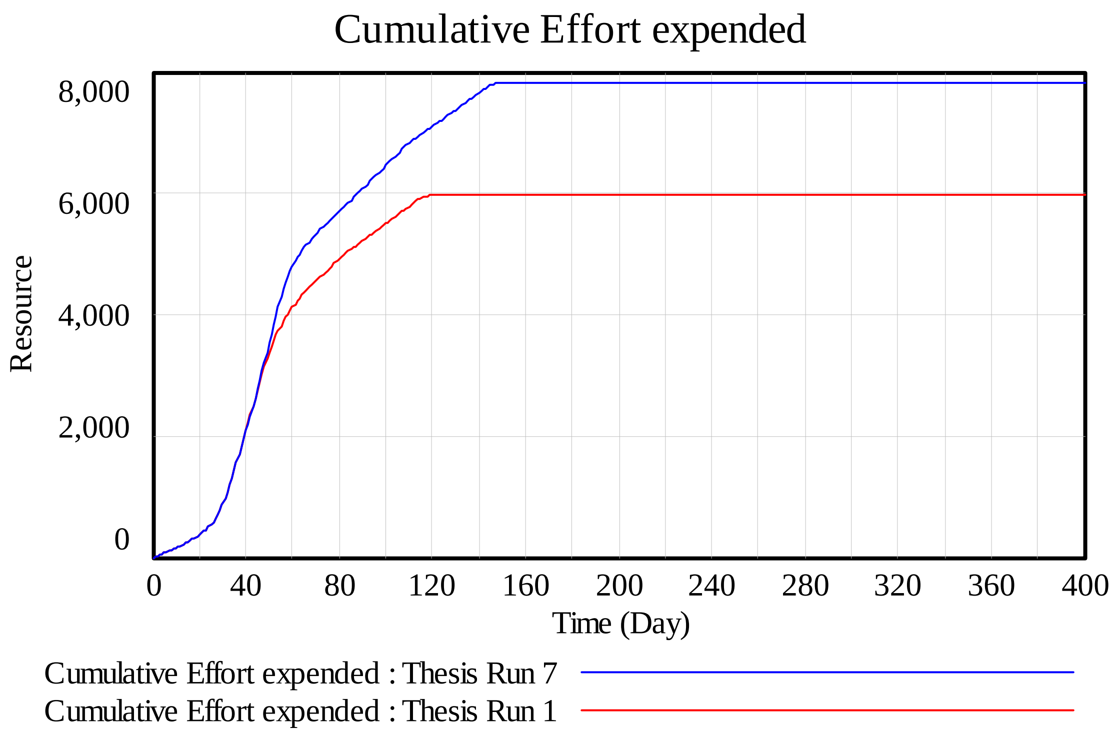

Figure 41: Cumulative Effort Expended Thesis Run 7 vs. Baseline

	Execution Quality	Resource Utilization	Information Flow Quality	Information Flow Delay	Exogenous Changes	Total Duration	Cumulative Work Done	Cumulative Effort Expended	Duration % Change	Work Done % Change	Effort Expended % Change
Units	-	-	-	*Days*	*Events*	*Days*	*Tasks*	*Resources*	-	-	-
Thesis Run 1	100%	100%	100%	0	0	160	100	5983.38	0%	0%	0%
Thesis Run 7	100%	100%	90%	4	2	189	130	7830	18%	30%	31%

Table 5: Thesis Run 7 vs. Baseline Data

5.3.5. Thesis Run 3 – Impact of Execution deficiencies and Exogenous Change events under perfect Information conditions

This simulation assumed:

- Execution Quality = 90%
- Resource Utilization = 90%
- Information Flow Quality = 100%
- Information Flow Delay = 0 Days
- Exogenous Change Events = 2

It established the impact of execution deficiencies and exogenous changes under perfect information conditions

- Total Duration = 201 days (+26%)
- Cumulative Work Done = 130 Tasks (+30%)
- Cumulative effort Expended = 8707 Resources (+46%)

This simulation serves as a basis of comparison for the impact of information factors when both execution deficiencies and exogenous changes are present.

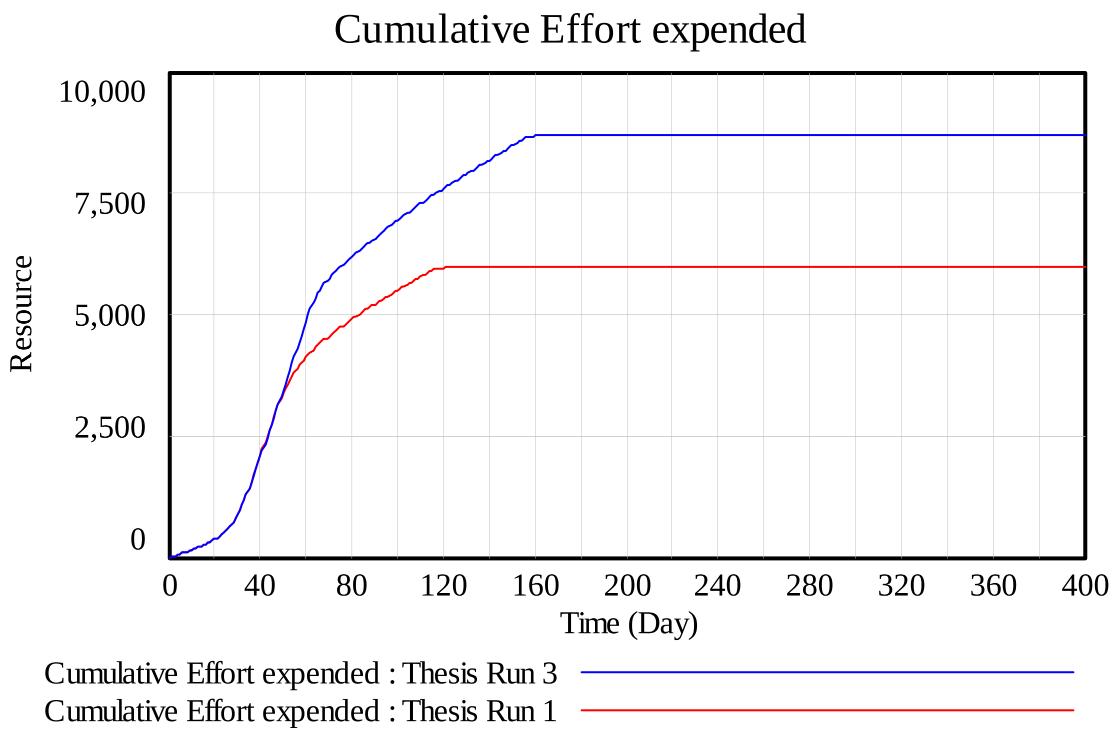

Figure 42: Cumulative Effort Expended Thesis Run 3 vs. Baseline

	Execution Quality	Resource Utilization	Information Flow Quality	Information Flow Delay	Exogenous Changes	Total Duration	Cumulative Work Done	Cumulative Effort Expended	Duration % Change	Work Done % Change	Effort Expended % Change
Units	-	-	-	*Days*	*Events*	*Days*	*Tasks*	*Resources*	-	-	-
Thesis Run 1	100%	100%	100%	0	0	160	100	5983.38	0%	0%	0%
Thesis Run 3	90%	90%	100%	0	2	201	130.467	8707.88	26%	30%	46%

Table 6: Thesis Run 3 vs. Baseline Data

5.3.6. Thesis Run 4 – Combined Impact of Execution deficiencies, Exogenous Change and Information Flow Deficiencies

This simulation assumed:

- Execution Quality = 90%
- Resource Utilization = 90%
- Information Flow Quality = 90%
- Information Flow Delay = 4 Days (2.5% of optimal Total Duration)
- Exogenous Change Events = 2

It established the combined impact of execution deficiencies, exogenous changes and information flow deficiencies.

- Total Duration = 235 days (+47%)
- Cumulative Work Done = 170 Tasks (+70%)
- Cumulative effort Expended = 11636 Resources (+94%)

Compared to the preceding simulation which assumed perfect information conditions we note a 21% increase in **Total Duration**, 40% increase in **Cumulative Work Done** and a 48% increase in **Cumulative Effort Expended**. Discounting the influence that information factors can have on resource replenishment and utilization, and their effect in conjunction with exogenous changes, the increase noted here can be attributed to the impact on **Rework Discovery** and a lower **Work Rate** due to **Information Quality Flow** effects on **Resource Utilization**.

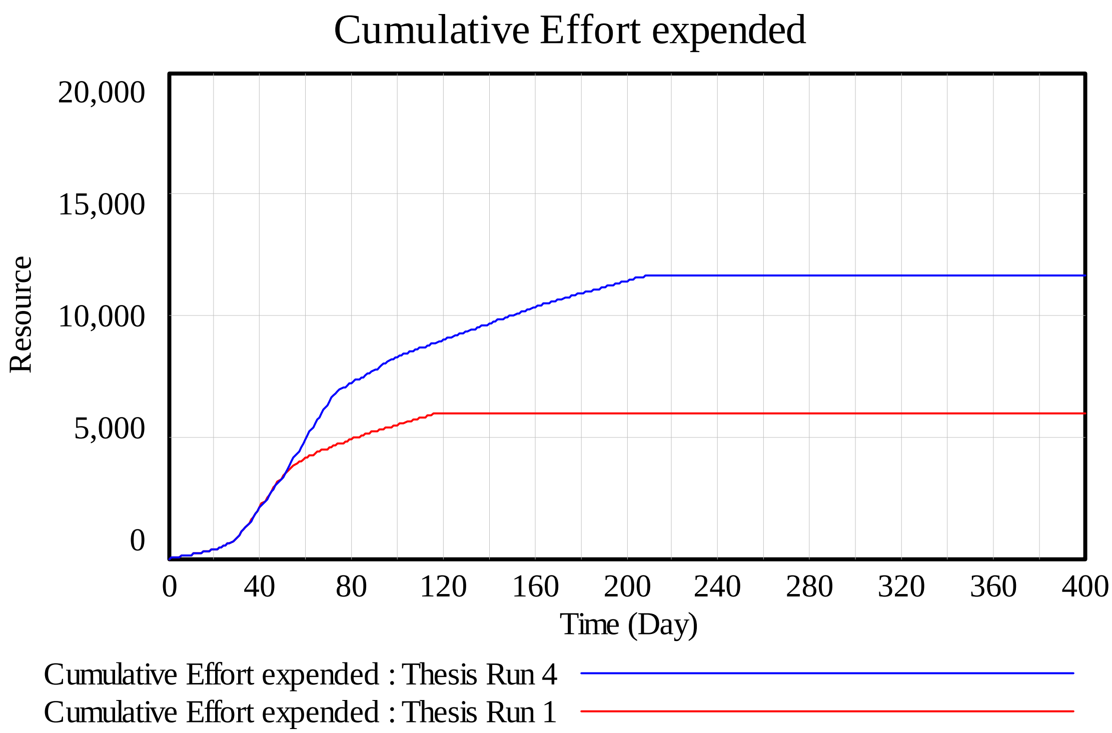

Figure 43: Cumulative Effort Expended Thesis Run 4 vs. Baseline

	Execution Quality	Resource Utilization	Information Flow Quality	Information Flow Delay	Exogenous Changes	Total Duration	Cumulative Work Done	Cumulative Effort Expended	Duration % Change	Work Done % Change	Effort Expended % Change
Units	-	-	-	*Days*	*Events*	*Days*	*Tasks*	*Resources*	-	-	-
Thesis Run 1	100%	100%	100%	0	0	160	100	5983.38	0%	0%	0%
Thesis Run 4	90%	90%	90%	4	2	235	170.053	11636.8	47%	70%	94%

Table 7: Thesis Run 8 vs. Baseline Data

5.3.7. Thesis Run 5 – Sensitivity Analysis of Information Flow Quality

This simulation assumed:

- Execution Quality = 90%
- Resource Utilization = 90%
- Information Flow Quality = 80%
- Information Flow Delay = 4 Days (2.5% of optimal Total Duration)
- Exogenous Change Events = 2

This simulation maintains all variables at the same level as ***Thesis Run 4*** except the **Information Flow Quality** is further reduced to 80%.

- Total Duration = 262 days (+64%)
- Cumulative Work Done = 170 Tasks (+70%)
- Cumulative effort Expended = 14353 Resources (+140%)

Compared to ***Thesis Run 4,*** the effect of reducing the **Information Flow Quality** by an additional 10% is a 17% increase in **Total Duration,** and a 46% increase in **Cumulative Effort expended**. This can be explained as a consequence of a reduction in the **Work Rate** due to the impact that **Information Flow Quality** has on **Resource Utilization**. Even though the **Cumulative Work Done** stays the same, it takes much longer to complete, because the **Available Resources** are consistently underutilized.

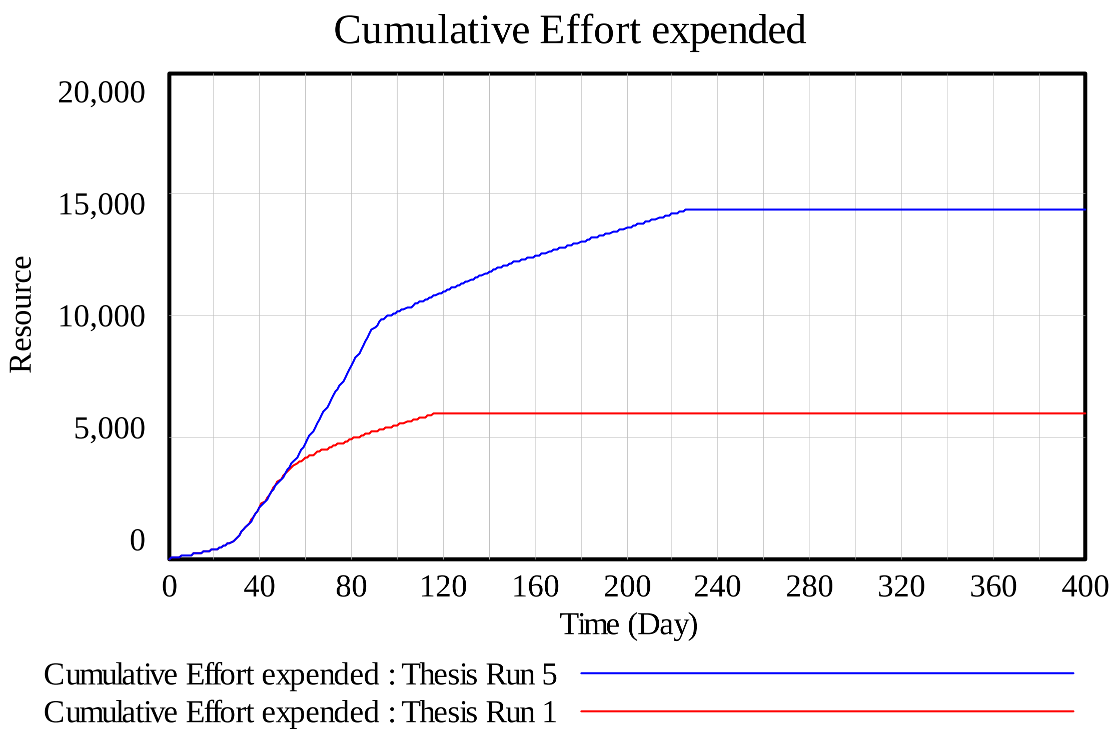

Figure 44: Cumulative Effort Expended Thesis Run 5 vs. Baseline

	Execution Quality	Resource Utilization	Information Flow Quality	Information Flow Delay	Exogenous Changes	Total Duration	Cumulative Work Done	Cumulative Effort Expended	Duration % Change	Work Done % Change	Effort Expended % Change
Units	-	-	-	*Days*	*Events*	*Days*	*Tasks*	*Resources*	-	-	-
Thesis Run 1	100%	100%	100%	0	0	160	100	5983.38	0%	0%	0%
Thesis Run 5	90%	90%	80%	4	2	262	170.007	14353.9	64%	70%	140%

Table 8: Thesis Run 5 vs. Baseline Data

5.3.8. Thesis Run 6 – Sensitivity Analysis of Information Flow Delay

This simulation assumed:

- Execution Quality = 90%
- Resource Utilization = 90%
- Information Flow Quality = 90%
- Information Flow Delay = 8 Days (5% of optimal Total Duration)
- Exogenous Change Events = 2

This simulation maintains all variables at the same level as ***Thesis Run 4*** except the **Information Flow Delay** is increased to 8 days (5% of optimal **Total Duration**).

- Total Duration = 315 days (+97%)
- Cumulative Work Done = 211 Tasks (+111%)
- Cumulative effort Expended = 14254 Resources (+138%)

Compared to the ***Thesis Run 4,*** the effect of increasing the **Information Flow Delay** by 4 more days is a 50% increase in **Total Duration**, a 41% increase in **Cumulative Work Done** and a 44% increase in **Cumulative Effort expended**. This can be explained as a consequence of the increase in **Time to Discover Rework** due to the impact that **Information Flow Delay** has on **Maximum Time to Discover Rework** and **Minimum Time to Discover Rework**. Late discovery of rework allows the accumulation of a far greater amount of rework, which it then takes longer and more effort to resolve.

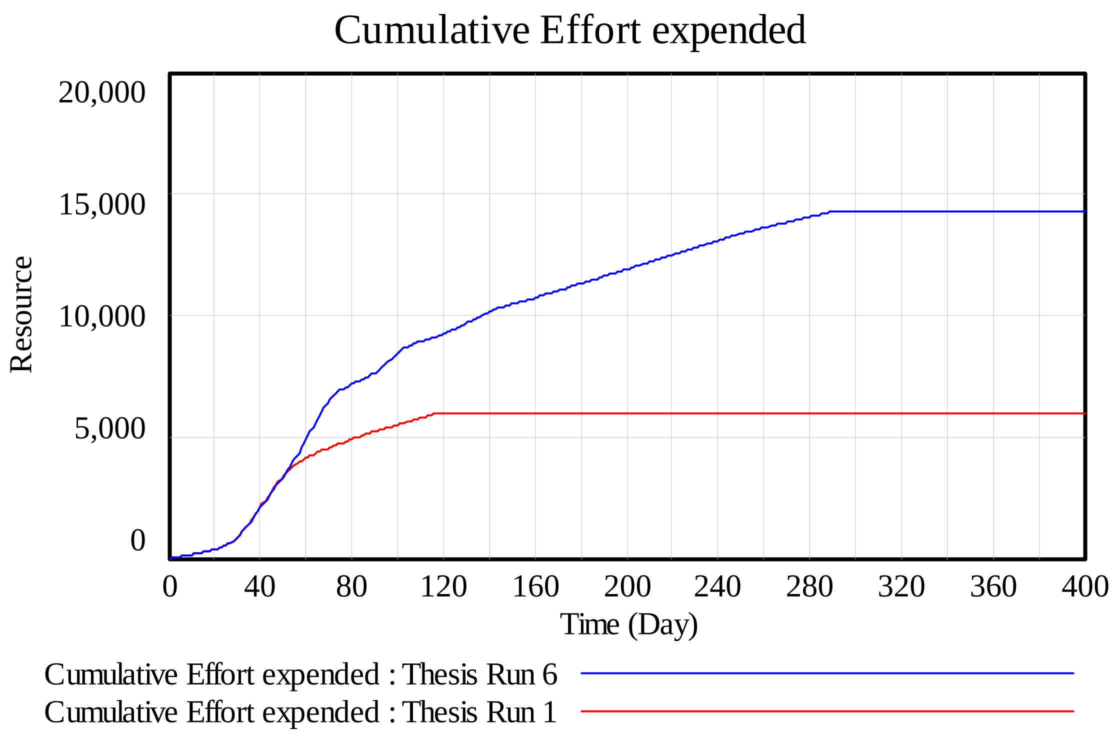

Figure 45: Cumulative Effort Expended Thesis Run 6 vs. Baseline

	Execution Quality	Resource Utilization	Information Flow Quality	Information Flow Delay	Exogenous Changes	Total Duration	Cumulative Work Done	Cumulative Effort Expended	Duration % Change	Work Done % Change	Effort Expended % Change
Units	-	-	-	*Days*	*Events*	*Days*	*Tasks*	*Resources*	-	-	-
Thesis Run 1	100%	100%	100%	0	0	160	100	5983.38	0%	0%	0%
Thesis Run 6	90%	90%	90%	8	2	315	211.371	14254.6	97%	111%	138%

Table 9: Thesis Run 6 vs. Baseline Data

5.4. Project Information Dynamics Conclusions

Correlating the dynamics that were established within the model with Process Failure manifestations we observe that:

- **Execution Quality** was a representation of **Agent, Instrument or Instrument System Errors**. ***Thesis Run 6*** demonstrated the importance of increasing the **Rework Discovery** rate as a means for mitigating the impact that such failures can have on the project. It should be noted that **Rework Discovery** is enabled by the performance of the **Assessing** function and the overall information flow rate on the project. Improving the performance in both areas is dependent upon better integration between the communication and assessing enablers at the process level with the project wide **Assessing** and **Communication Systems**.

- **Resource Utilization** was a representation of **Agent, Instrument or Instrument System Inefficiency** while the influence of **Information Flow Quality** represented **Interaction Error**. ***Thesis Run 5*** demonstrated how much of an impact such inefficiencies can have on project duration and the amount of effort that is wasted as consequence. It is therefore evident that operational improvements in these process as well as information flow quality improvements can play an important role in mitigating the associated process failures.

- **Resource Replenishment** represented an **Interaction Inefficiency**. The impact demonstrated in ***Thesis Run 8*** was partly due to this effect. It should be noted however, that the fact that the **Resource Mobilization Plan** was designed to ensure that enough staff was on hand and that resources were not allowed to be shed until they had been utilized had a part to play in dampening the impact demonstrated. A comparison of ***Thesis Run 1 (Baseline)*** values for **Cumulative Effort Expended** against **Cumulative Required Resources** revealed a 61% excess in resources utilized. This demonstrates that efficient resource logistics could potentially garner significant savings for a project.

- The dynamics representing **Exogenous Changes in Requirements** represented the product failure manifestation of the same name. ***Thesis Run 7*** was able to demonstrate how information flow factors can significantly compound the effect that such changes can have on a project, thus supporting the argument that strengthening the **Requirements Engineering** process would help mitigate this impact.

Overall the System Dynamics model was able to support the argument that information flow represents a critical factor for overall project performance, as well as mitigation of project failures.

6. Thesis Conclusions

6.1. Summary of Findings

The Project System model and the associated analysis yielded the following insights:

- An understanding of the types of the basic processes that must exist within a Project System. Their purpose, their needed inputs and outputs and the role they play in the information transfer system
- An examination of information types, flow factors and the critical importance of minimizing information asymmetry to generate Project System efficiency. This was later demonstrated by developing the **Project Information Dynamics** model using System Dynamics.
- A study of the formal elements (i.e. **Contextual Artifacts**) and the role that their components and attributes play on the ability of individual project processes to function effectively (i.e. **Requisite Abilities**); which was the basis of a methodology for process improvements that could be applied to any process in a project: **Systems Approach to Process Improvement**
- Finally an understanding of failure modes and their manifestations and an illustration of how this process improvement methodology could be applied to mitigate their occurrence.

Collectively these elements led to what is probably the most significant take away from this thesis. There is basic tenant of architecture that form should follow function. The functional analysis of the Project System brought forth the following realizations:

- That every process within the Project System must be able to send and receive information:
    - Either to seek or send instructions
    - Interact with other participants
    - To enable its own monitoring.
- The motivation of a participant to exert effort varies for each process
- The degree of interaction and cooperation needed varies for each process

Therefore, the formal structure adopted to enable each process must not only be capable of fulfilling its primary function, but must also be customized to fulfill its communication, incentivizing and interactive needs. This insight not only led to the development of the **Systems Approach to Process Improvements** but also reflects a fundamental shift in two areas from how Project Management is typically approached in practice:

1) Delegating the management of project wide communications and assessment responsibilities to a project wide functional groups

2) Defining incentives and interaction protocols on a participant basis rather than a task basis

This thesis argues instead that if the enterprise objectives of communication and assessment abilities were embedded into the formal elements responsible for each process this would significantly improve overall information flow. If we refer to our earlier observation that there are limits to our ability to predict which issues are likely to afflict a project, and to what degree, the uniform reduction of information asymmetry that this approach engenders would improve a project's ability to mitigate failures.

Furthermore, the agreements and the organizational structure, which govern the distribution of incentives and the protocols for interaction, must take the varying needs and context of the specific processes which they encompass.

6.2. Further Research

6.2.1. Lean Project Management

One of the inspirations for pursuing a **Systems Approach to Process Improvements** in the context of **Project Systems** was a desire to enable the application of Lean Manufacturing principles to Project Management.

In terms of the basic principles of Lean thinking[9], the intrinsic value of

- Reducing waste through greater efficiency and effectiveness
- By focusing on integration of stakeholders and the application of individual process improvements
- While retaining a holistic perspective of the Enterprise objectives

[9] Murman, Earll. Allen, Thomas. et al. "Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative". Palgrave. (2002)

is self evident in the context of Project Management. Unfortunately, the methodologies that have been developed to implement these goals in a manufacturing setting do not translate quite as effectively into a project setting.

The most significant differences that I have observed are that while in manufacturing you are essentially dealing with a series of repetitive processes, a project is comprised of a set of individual tasks, many of which will not be repeated again. This means that the benefits that can be derived from operations optimization and supply chain optimization methodologies will only go so far in the project setting. Beyond that a project has a far greater need for flexibility and agility to deal with one-time tasks and a constantly changing environment.

Furthermore, the relationships between departments or independent firms within the manufacturing sector tend to be long term, which not only gives time for improving integration but also engenders a vested interest amongst the parties involved to seek out process improvements for mutual benefit. In contrast, the relationships amongst project participants tend to be short term. With no guarantees of there being any relationship beyond the duration of the project, all parties tend to focus on maximizing their own profits and minimizing their own risks, at the expense of one another if necessary.

These differences do not diminish the value of information flow, or the need to stimulate integration between participants as means for reducing waste in either of the business models. Rather they highlight that the methodologies for achieving these objectives have to be customized for the business models accordingly.

In recent years the concept of Lean Project Management has been gaining ground, though it has yet to develop a comparable set of Lean Methodologies for Project Management as we see for Manufacturing. The **Systems Approach to Process Improvements** could potentially be refined into one of the methodologies that would constitute such a toolkit. And while there are certainly some methodologies already in use within manufacturing that could readily be adopted by Project Management, the system analysis portion of the thesis illustrates some of the characteristics that are unique to the project environment which could aid in the development of other more project specific methodologies.

6.2.2. Project Information Dynamics Model

The **Project Information Dynamics** model presented in this thesis is, in my opinion, a work in progress. There were a number of additional project related dynamics that were considered but had to be left out due to lack of time. Their inclusion in the model would significantly improve its depiction of **Project System** dynamics.

- **Product Failure:** The only Product Failure manifestation currently included in the model is an Exogenous Change in Requirements which has the effect of adding additional work into the scope. However, the impact of a Requirements Engineering Failure could also be included as a temporary reduction in **Execution Quality** thereby generating additional rework during its period of impact.

- **Rework Discovery:** The current model assumes that the only impact of Errors is the repetition of work that has previously been completed. In reality, depending on the type of work that is being pursued, the actual impact of an Error can be quite different from what is depicted in the model. In the case of Design work or Software Engineering a learning-curve effect may mean that rework iterations actually take less time and effort than it took to do a task the first time. Conversely in a Construction environment rectifying an Error can also entail some Undoing work before Rework can commence.

- **Multiple Scopes of Work**: Many projects have distinct divisions in the scope of work that can be pursued either sequentially or in parallel (e.g. Design plus Construction). Furthermore it is possible that these portions of the total work may be assigned to independent firms. Developing the model to allow for modeling such projects and the associated inter-firm interaction dynamics would constitute an interesting area of research.

- **Information Flow Factors:** The current model couples the impact of Bandwidth and Noise factors into the single variable: **Information Flow Quality**. It may be worth while to separate these two factors given that their impact on information asymmetry can be quite different. While an increase in Noise can be expected to always result in an increase in information asymmetry, Bandwidth is likely to have an optimal amount at which information asymmetry is at a minimum. This is based on the premise that it is possible to have an information overload, such that in spite of having a great deal of information the ability to process it becomes the cause of information asymmetry.

- **Resource Management Efficiencies:** The model unexpectedly demonstrated through its Resource Replenishment dynamic how much of an impact a resource mobilization strategy can have on total effort expended and consequently on overall costs. I believe that this is a portion of the model that needs to be developed further to study the cost saving potential of different resource management strategies.

7. References

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Appendix I – Project Information Dynamics – Model Documentation

Complete Model Diagram:

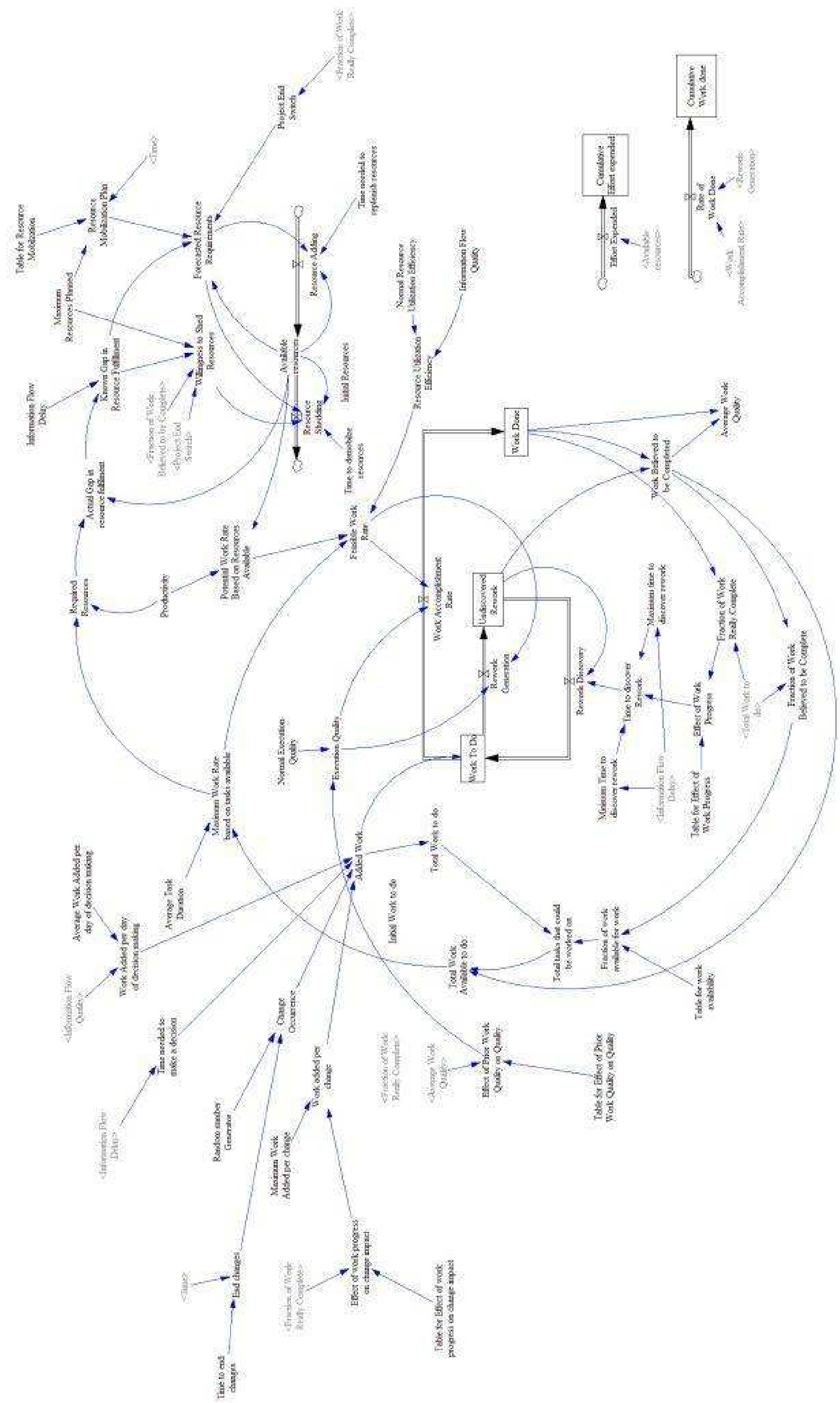


Figure 46: Project Information Dynamics Model

Model Text File:

```
End changes=

      IF THEN ELSE(Fraction of Work Really Complete<0.6,1,0)*IF THEN
ELSE(Time>100,0,1)

      ~     Dmnl

      ~           |

Willingness to Shed Resources=

      IF THEN ELSE(Known Gap in Resource Fulfillment/Maximum Resources
Planned<-0.1,1,0)*IF THEN ELSE\

            (Fraction of Work Believed to be Complete>0.6,1,0)+(1-
Project End Switch)

      ~     Dmnl

      ~           |

Resource Shedding=

      ((Forecasted Resource Requirements-Available resources)/Time to
demobilze resources)\

            *Willingness to Shed Resources

      ~     Resource/Day

      ~           |

Available resources= INTEG (

      Resource Adding+Resource Shedding,

            Initial Resources)

      ~     Resource

      ~           |

Time to demobilze resources=

      5

      ~

      ~           |
```

```
Forecasted Resource Requirements=

	(IF THEN ELSE(Known Gap in Resource Fulfillment<0,Resource
Mobilization Plan,Available resources\

		+ Known Gap in Resource Fulfillment))*Project End Switch

	~	Resource

	~		|

Resource Adding=

	Max((Forecasted Resource Requirements-Available resources)/Time
needed to replenish resources\

		,0)

	~	Resource/Day

	~		|

Table for Effect of work progress on change impact(

	[(0,0)-
(1,2)],(0,1),(0.1,1.03),(0.2,1.06),(0.3,1.1),(0.4,1.15),(0.5,1.2),(0.6,1
.25),\

		(0.7,1.3),(0.8,1.4),(0.9,1.6),(1,2))

	~	Dmnl

	~		|

Maximum Work Added per change=

	5

	~	Tasks

	~		|

Effect of work progress on change impact=

	Table for Effect of work progress on change impact(Fraction of
Work Really Complete)

	~	Dmnl

	~		|

Work added per change=

	Maximum Work Added per change*Effect of work progress on change
impact
```

```
	~	Tasks
	~		|

Project End Switch=
	IF THEN ELSE(Fraction of Work Really Complete>0.99,0,1)
	~	Dmnl
	~		|

Change Occurrence=
	IF THEN ELSE(Random number Generator>97,1,0)*End changes
	~	Dmnl
	~		|

Rate of Work Done=
	Rework Generation+Work Accomplishment Rate
	~	Tasks/Day
	~		|

Cumulative Work done= INTEG (
	Rate of Work Done,
		0)
	~	Tasks
	~		|

Actual Gap in resource fulfilment=
	Required Resources-Available resources
	~
	~		|

Known Gap in Resource Fulfillment=
	DELAY FIXED(Actual Gap in resource fulfilment,Information Flow
Delay, Actual Gap in resource fulfilment\
		)
	~	Resource
```

```
	~		|

Effect of Work Progress=

	Table for Effect of Work Progress (Fraction of Work Really 
Complete)

	~	Dmnl

	~		|

Resource Mobilization Plan=

	Table for Resource Mobilzation(Time)*Maximum Resources Planned

	~	Resource

	~		|

Initial Resources=

	13

	~	Resource

	~		|

Normal Execution Quality=

	0.9

	~	Dmnl

	~		|

Added Work=

	(Change Occurrence*Work added per change)+(Change Occurrence*Time 
needed to make a decision\

		*Work Added per day of decision making)

	~	Tasks

	~		|

Time to discover Rework=

	Maximum time to discover rework * Effect of Work Progress + (1-
Effect of Work Progress\

		) * Minimum Time to discover rework

	~	Day
```

```
	~		|

Average Work Added per day of decision making=

	1

	~

	~		|

Average Work Quality=

	Max(1e-006,Work Done)/Max(1e-006, Work Believed to be Completed)

	~	Dmnl

	~		|

Information Flow Quality=

	0.9

	~	Dmnl

	~		|

Cumulative Effort expended= INTEG (

	Effort Expended,

		0)

	~	Resource

	~		|

Effect of Prior Work Quality on Quality=

	Table for Effect of Prior Work Quality on Quality(Average Work
Quality)

	~	Dmnl

	~		|

Effort Expended=

	Available resources

	~	Resource

	~		|
```

```
Execution Quality=

      Effect of Prior Work Quality on Quality*Normal Execution Quality

      ~     Dmnl

      ~           |

Time needed to make a decision=

      Information Flow Delay*2

      ~     Day

      ~           |

Normal Resource Utilization Efficiency=

      0.9

      ~     Dmnl

      ~           |

Maximum Resources Planned=

      130

      ~     Resource

      ~           |

Fraction of Work Really Complete=

      Work Done/Total Work to do

      ~     Dmnl

      ~           |

Information Flow Delay=

      5

      ~     Day

      ~           |

Table for Resource Mobilzation(

      [(0,0)-
(400,1)],(0,0.1),(10,0.15),(20,0.2),(30,1),(40,0.8),(50,0.4),(60,0.25),(
70,0.22\
```

```
            ),(80,0.22),(90,0.15),(400,0.15))

      ~     Dmnl

      ~           |

Minimum Time to discover rework=

      IF THEN ELSE(Information Flow Delay*4=0,4,Information Flow
Delay*4)

      ~     Day

      ~           |

Maximum time to discover rework=

      IF THEN ELSE(Information Flow Delay*8=0,8,Information Flow
Delay*8)

      ~     Day

      ~           |

Table for Effect of Work Progress(

      [(0,0)-
(1,1)],(0,1),(0.1,1),(0.2,1),(0.3,1),(0.4,1),(0.5,0.9),(0.6,0.75),(0.7,0
.5),(\

            0.8,0.25),(0.9,0.1),(1,0))

      ~     Dmnl

      ~           |

Resource Utilization Efficiency=

      Normal Resource Utilization Efficiency*Information Flow Quality

      ~     Dmnl

      ~           |

Table for Effect of Prior Work Quality on Quality(

      [(0,0)-
(10,10)],(0,0.05),(0.1,0.1),(0.2,0.2),(0.3,0.3),(0.4,0.4),(0.5,0.5),(0.6
,0.6)\

            ,(0.7,0.7),(0.8,0.8),(0.9,0.9),(1,1))

      ~     Dmnl

      ~           |
```

```
Work Added per day of decision making=
	Average Work Added per day of decision making*(2-Information Flow
Quality)
	~	Day
	~		|

Total tasks that could be worked on=
	Total Work to do*Fraction of work available for work
	~	Tasks
	~		|

Fraction of Work Believed to be Complete=
	Work Believed to be Completed/ Total Work to do
	~	Dmnl
	~		|

Work To Do= INTEG (
	Rework Discovery-Rework Generation-Work Accomplishment Rate+Added
Work,
		Initial Work to do)
	~	Tasks
	~		|

Total Work to do= INTEG (
	Added Work,
		Initial Work to do)
	~	Tasks
	~		|

Random number Generator=
	RANDOM UNIFORM(0,100,1)
	~	Dmnl
	~		|
```

```
Initial Work to do=
      100
      ~
      ~           |

Rework Discovery=
      Undiscovered Rework/Time to discover Rework
      ~     Tasks/Day
      ~           |

Undiscovered Rework= INTEG (
      Rework Generation-Rework Discovery,
            0)
      ~     Tasks
      ~           |

Work Accomplishment Rate=
      Feasible Work Rate*Execution Quality
      ~     Tasks/Day
      ~           |

Feasible Work Rate=
      min(Maximum Work Rate based on tasks available,Potential Work Rate
Based on Resources Available\
            )*Resource Utilization Efficiency
      ~     Tasks/Day
      ~           |

Time needed to replenish resources=
      5
      ~     Day
      ~           |

Average Task Duration=
```

```
	5
	~	Day
	~		|

Total Work Available to do=
	Max(0,Total tasks that could be worked on-Work Believed to be
Completed)
	~	Tasks
	~		|

Table for work availability(
	[(0,0)-
(1,1)],(0,0.01),(0.1,0.14),(0.2,0.34),(0.25,0.48),(0.4,0.55),(0.5,0.6),(
0.6,0.66\
		),(0.7,0.74),(0.8,0.83),(0.9,0.92),(0.98,1),(1,1))
	~	Dmnl
	~		|

Fraction of work available for work=
	Table for work availability(Fraction of Work Believed to be
Complete)
	~	Dmnl
	~		|

Work Done= INTEG (
	Work Accomplishment Rate,
		0)
	~	Tasks
	~		|

Potential Work Rate Based on Resources Available=
	Available resources*Productivity
	~	Tasks/Day
	~		|
```

```
Maximum Work Rate based on tasks available=

      Total Work Available to do/Average Task Duration

      ~     Tasks/Day

      ~           |

Rework Generation=

      Feasible Work Rate*(1-Execution Quality)

      ~     Tasks/Day

      ~           |

Required Resources=

      Maximum Work Rate based on tasks available/Productivity

      ~     Resource

      ~           |

Work Believed to be Completed=

      Work Done+Undiscovered Rework

      ~     Tasks

      ~           |

Productivity=

      0.03

      ~     Tasks/(Resource*Day)

      ~           |

********************************************************

      .Control

********************************************************~

            Simulation Control Parameters

      |

FINAL TIME  = 400

      ~     Day
```

```
	~	The final time for the simulation.
	|

INITIAL TIME  = 0
	~	Day
	~	The initial time for the simulation.
	|

SAVEPER  = 
        TIME STEP
	~	Day [0,?]
	~	The frequency with which output is stored.
	|

TIME STEP  = 1
	~	Day [0,?]
	~	The time step for the simulation.
	|
```

Simulation Results:

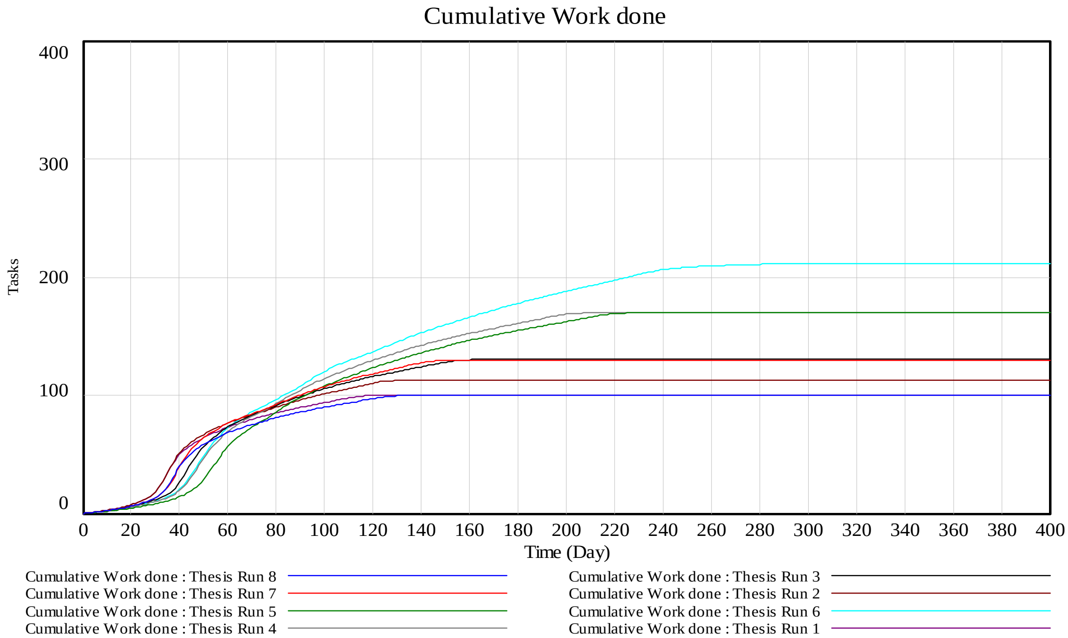


Figure 47: Cumulative Work Done Comparative Chart

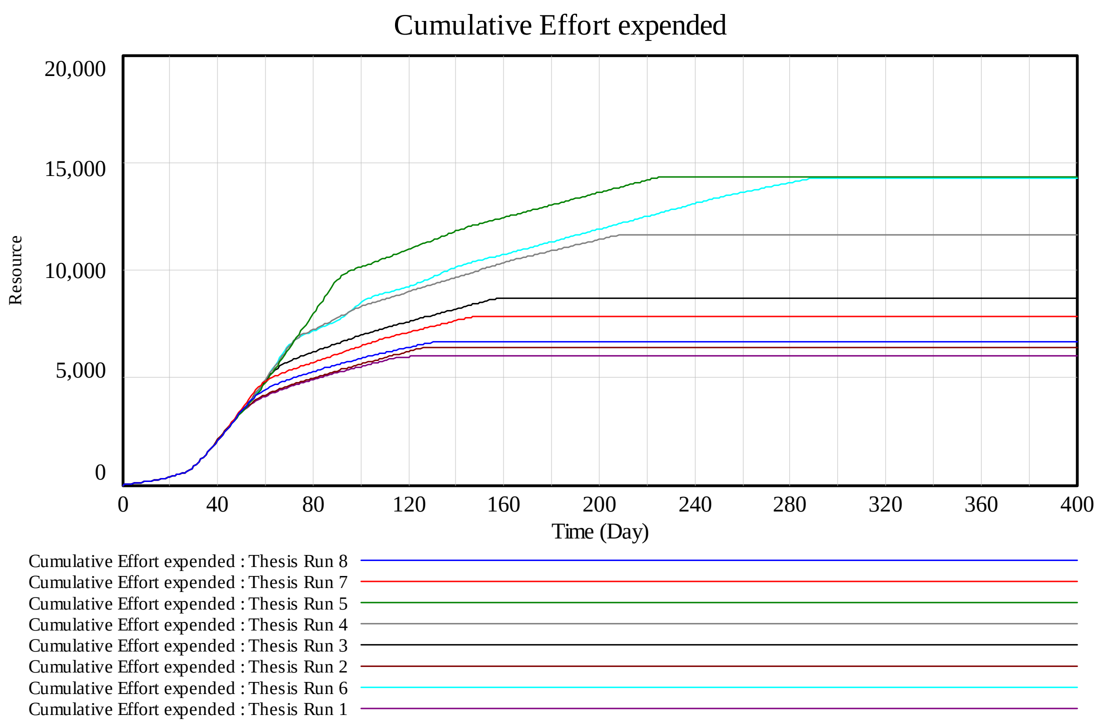


Figure 48: Cumulative Effort Expended Comparative Chart

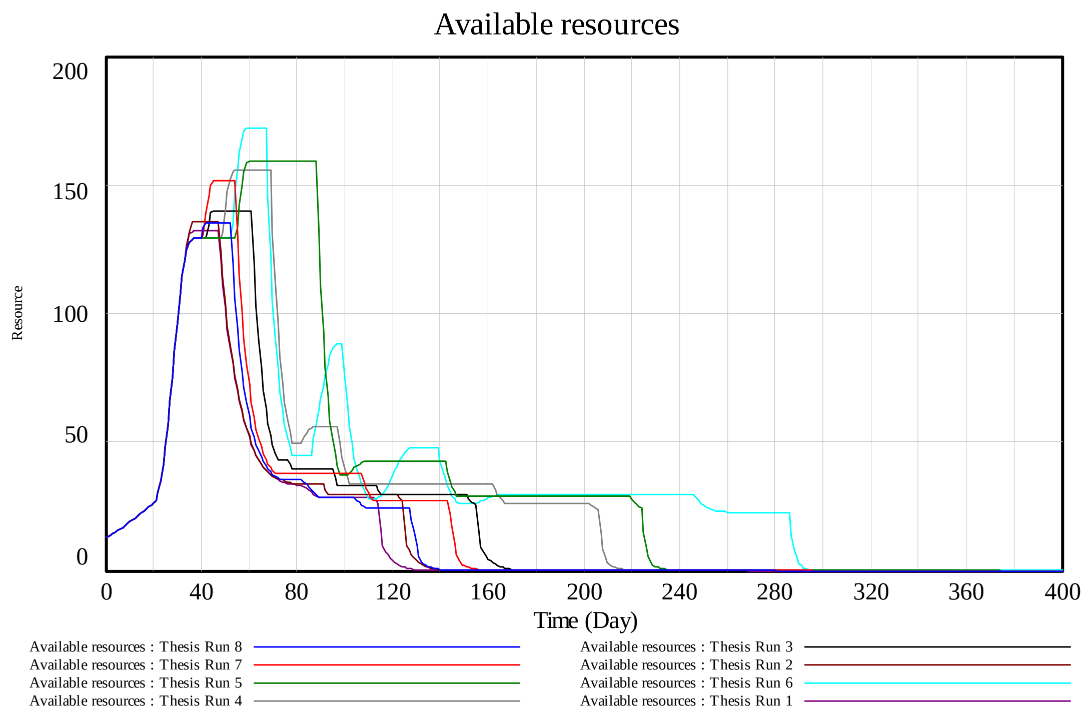
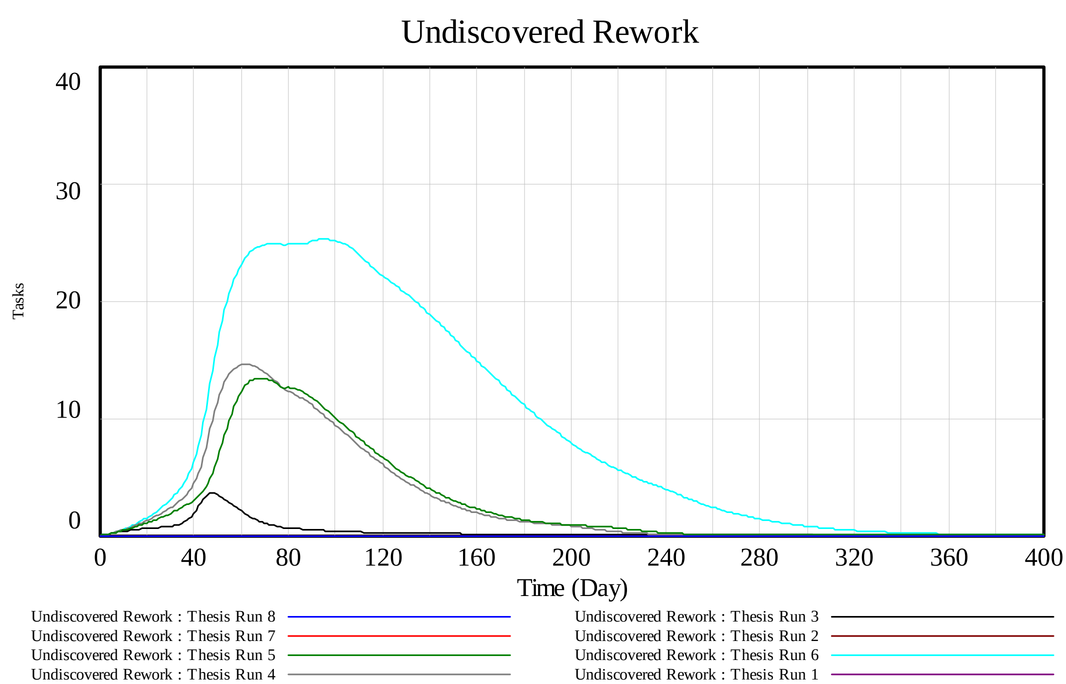


Figure 49: Available Resources Comparative Chart



	Execution Quality	Resource Utilization	Information Flow Quality	Information Flow Delay	Exogenous Changes	Total Duration	Cumulative Work Done	Cumulative Effort Expended	Duration % Change	Work Done % Change	Effort Expended % Change
Units	-	-	-	*Days*	*Events*	*Days*	*Tasks*	*Resources*	-	-	-
Thesis Run Test	100%	100%	100%	0	0	160	100	3703.7			
Thesis Run 1	100%	100%	100%	0	0	160	100	5983.38	0%	0%	0%
Thesis Run 2	100%	100%	100%	0	2	168	112.656	6420.04	5%	13%	7%
Thesis Run 8	100%	100%	90%	4	0	166	100	6662	4%	0%	11%
Thesis Run 7	100%	100%	90%	4	2	189	130	7830	18%	30%	31%
Thesis Run 3	90%	90%	100%	0	2	201	130.467	8707.88	26%	30%	46%
Thesis Run 4	90%	90%	90%	4	2	235	170.053	11636.8	47%	70%	94%
Thesis Run 5	90%	90%	80%	4	2	262	170.007	14353.9	64%	70%	140%
Thesis Run 6	90%	90%	90%	8	2	315	211.371	14254.6	97%	111%	138%

Table 10: Simulations Comparative Data