Spring 2020

Application of Theory of Constraints (ToC) in Managing Project Information Constraints

Ferdinand Z. Prantl
Old Dominion University, fdprantl@cox.net

APPLICATION OF THEORY OF CONSTRAINTS (TOC) IN MANAGING PROJECT INFORMATION CONSTRAINTS

by

Ferdinand Z. Prantl
B.S. June 1981, American University in Cairo, Egypt
M.S August 2002, Old Dominion University

A Dissertation Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of
the Requirements for the Degree of

DOCTOR OF ENGINEERING

ENGINEERING MANAGEMENT

OLD DOMINION UNIVERSITY
February 2020

Approved by:

C. Ariel Pinto (Advisor)

Steven Cotter (Member)

Luna Magpili (Member)

Rafael Landaeta (Member)

ABSTRACT

APPLICATION THEORY OF CONSTRAINTS (TOC) IN MANAGING PROJECT INFORMATION CONSTRAINTS

Ferdinand Z. Prantl
Old Dominion University,2020
Director: Dr. C. Ariel Pinto

The scope of this doctoral project is the non-traditional application of Drum-Buffer-Rope (DBR) from the area of Theory of Constraints (ToC) in mitigating disruption in distribution facilities during phased upgrades caused by information constraint. The relevance of this project is that industrial equipment upgrades pose a significant risk of disrupting the operation of automated distribution facilities. It is partly due to a very high expected availability rate, as well as tight coupling with other upstream and downstream elements of the larger supply chain network. As a consequence of disruption in this scenario, losses incurred not only within the facility being upgraded but also to the entire supply chain, as well. This project will particularly examine the potential non-traditional application of DBR. It is to mitigate risk brought by unavailable timely information during equipment upgrade by treating the information-time issue as a constraint that can then be elevated among various stakeholders and into the equipment upgrade schedule. This project contributes to the advancement of engineering management and project management practice in obtaining the appropriate information and data to minimize disruption posed by information-time constraint.

Keywords

Theory of Constraints, DBR, Information, Risk, statistical fluctuation

This doctoral project is dedicated to my wife Donna for her support, encouragement and patience. Her inspiration encouraged me to reach this goal. I also want to dedicate it to my son Drew and his wife Jessica and my sisters for their encouragement.

ACKNOWLEDGMENTS

I would like to thank Dr. C. Ariel Pinto for his dedication and guidance. He was always encouraging even in the moments of disparity. Dr. C. Cotter for his enthusiasm and pointing me in the right direction when I was going off the path. Dr. L. Magpili for pointing out the nuances of ToC and challenging me to dig deeper. Lastly, I appreciate Dr. R. Landaeta for being a part of the committee. All your dedication made it possible for me to achieve my goal.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF EXHIBITS

CHAPTER 1

STUDY INTRODUCTION

1.1. Study Introduction

Information is what makes or breaks a project, especially when upgrading industrial facilities. The most readily accessible information is found in the contracts between the customer and the company performing the upgrade. This information sets goals to improve the facility's performance, such as increasing the throughput, reduction of waste, increase in efficiency, etc. and are the apparent criteria in designing the upgrade. Most contracts include a clause that the upgrade activity should have no or minimal disruption to the daily operations, and yet the implementation process is not found. Such a disruption could have serious economic implications. This becomes obvious when dealing with automated distribution centers that supply goods to retail stores.

Updating and renovating equipment in automated distribution centers or even factories is the cause of stoppage in production in the area that is updated. It is caused by dismantling old equipment and installing new ones, and during this time, production in that area comes to a halt. For the large supply chain, this results in diminished or worse, the absence of the output of goods to the market, and, in return, causes economic losses. Some industries can absorb such losses, but others cannot. It especially evident in the retail sector since their profit margins are historically low (Deloitte, 2011), and they depend on the sales volume to reach the earnings they look for. It is the reason why retail companies, such as Wal-Mart, Target, etc., are concerned continuously of having half-empty-looking shelves in their stores or, worse, running out of merchandise. Half-empty and empty shelves are known factors for customers to buy less than they would if the shelves were full. Replenishing store shelves must be timed, so the quantities on the shelves never fall below a level which gives the impression that the store is running out of merchandise. Such conditions impact the store's buying atmosphere, as the customers do not find what they primarily wanted, and this, in return, inhibits their impulse buying behavior. The store atmosphere is the most significant contributor to impulse buying (Kacen, Hess, & Walker, 2012). Nonetheless, replenishing the store shelves with the needed merchandise becomes challenging, especially when many of the merchandise which can spur suggestive (or impulsive) buying has a limited shelf life, such as milk and other dairies (Stern, 1962). Up to fifty percent of retail merchandise is sold on impulse, as documented by the Du Pont study (Stern, 1962) (Kollat & Willet, 1969).

How does one ensure the constant flow of merchandise to the stores during a distribution center’s upgrade? This paper will show that the upgrading of industrial facilities, especially distribution centers, can be accomplished without impacting the flow of goods severely, and this can only be achieved by understanding the environment in which such an upgrade will take place. To appreciate the challenge, one must first have an understanding of how an automated distribution function.

1.2. Operation of a Distribution Center

An automated distribution center consists of multiple types of equipment supported by various types of control software and databases. Merchandise loaded on pallets is unloaded from trucks onto conveyors after being tagged with barcode labels and goes through an automated conformity station for identification, weight, and size checking. The merchandise is then assigned a rack in the warehouse by the Warehouse Management software (Warehouse Manager) and sends the information to the database system. The conveying system transports it to SRMs (Storage and Retrieval Machines), which are cranes that put pallets automatically into the designated rack.

Later, these pallets are retrieved automatically and placed in stations for the pickers to pick the orders for the various stores. The picking operation is often semi-automated, as a computerized system directs human pickers on what to pick, the sequence, and the quantity. The system that supports all these operations is governed by a database system that interfaces with the warehouse management system. The warehouse management system, in turn, interfaces with the various equipment control systems. The equipment control systems control the various mechanical and electric equipment. Exhibit 1 shows the dependency relationship between the four areas that govern the distribution center. Any one of these four areas has a potential impact on the rest of them, i.e., any positive or negative change will resonate throughout the system.

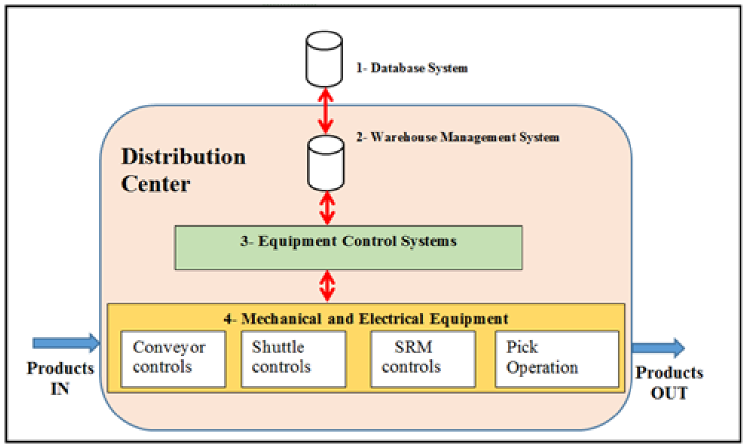

Exhibit 1 The Four Technical Areas of Operating an Automated Distribution Center.

1.3. Unknowns in Upgrade of Distribution Centers

At first glance, it seems upgrading an area of a distribution center is clear, as the equipment to be replaced is a known entity, hence it may be viewed as a purely technical issue. Ideally, entire equipment is dismantled and replaced on the spot and in one long period, but this means the area will be nonfunctional until the upgrade is completed. This is not realistic, as it would impact the output of the facility negatively. The upgrade must be accomplished with minimal impact on the productivity of the facility. Now, this does not make it a purely technical issue anymore, as it has to be accomplished in phases, where new and old equipment has to function smoothly until the upgrade is completed.

1.4. Phased Upgrade of Distribution Centers

A way to reduce the potential negative impact of an upgrade is by coordinating the upgrade activity with the operational activity of the facility. Not all areas in such facilities operate 24 hours a day. Certain areas are idle for some time; for example, goods are inducted into the system starting in the afternoon up to early in the morning, as this is the time trucks deliver their goods. That means the induct area is idle during the morning up to the afternoon. During this time, upgrading the induct area proceeds, but it is not possible to upgrade the whole area at once. It is only possible to upgrade the equipment in that area in phases. At the end of each phase, the area has to function to its nominal capacity. Planning such activity involves both the retail company as well as its various vendors that built, operate, maintain, and improve the distribution centers. Together, these various parties become an amalgamation of engineering, trade disciplines, and various business (non-technical) departments who all have to work in coordination to minimize the impact on the workflow and schedule of the distribution center. It involves a deep understanding of the technical aspects of the equipment being upgraded, the system which this equipment are parts of, and the business impacts of each during the performance of the upgrade. This multiparty business model produces many 'unknowns' - information relevant to the phased upgrade that is tacit, known to one or only a few parties, and unknown to many of the various parties involved.

A phased upgrade means that, for example, a conveyor line cannot be replaced in its entirety at once, but every day in the time slot designated for the work, one or two conveyors are replaced. At the end of the timeslot, they must function with the older conveyors, so production is not disrupted. The challenge is how to integrate the new conveyors with the old until the entire line is upgraded. This scenario has many unknowns, some of which are:

- New technology has to be incorporated into the existing system
- The condition of the current system is not fully known
- Documentation about the system does not show changes done over the years

How to incorporate the upgrade activity with the customer's workflow in order not to disrupt their operation is a challenge. These unknowns will cause major disruptions to the upgrade activity. It has become an 'unknown' information management issue. The unknowns are primarily the tacit information of changes that have taken place since the inception of the facility. They reside with various individuals, e.g., operators, maintenance personnel, software developers, IT administrators, managers, etc. These individuals have a stake in the phased upgrade, and each of them, whatever their function may be, must be considered a stakeholder. They all have made changes to their system in the arena of process, hardware, information technology, etc. to improve the efficiency of their daily operation. One cannot consider pieces of information in isolation, but one has to bring the perspective of all stakeholders associated with the system and manage the information collected from them (Cook & Ferris, 2007). However, each one may only know the changes that they or their immediate group have implemented, but not necessarily what others have implemented. Performing phased upgrade only with explicit information from legacy sources (e.g., blueprints, user-manuals, original technical specifications, etc.) and ignoring the unknowns could be negligence. Even more, the unknowns would be most informative to managing the risk of the phased upgrade project, and finding them takes time and effort and becomes the constraint or a bottleneck that slows the technical progress of such a project.

1.5. Definition of Bottleneck Across Disciplines

In different disciplines, the understanding of what a bottleneck is is not the same. In information theory, the understanding is that existing information is forced through a restricted pathway slowing down the transmission of the information. This can be equated to traffic on a highway, where cars go from three lanes and have to squeeze through a single lane. A solution in information theory has been developed in the 1990s by Naftali Tishby, Fernando C. Pereira, and William Bialek who called it the information bottleneck method (Tishby, Pereira, & Bialek, 2000). They solved the problem of passing data through a constraint, better known as a bottleneck, without losing information and at an acceptable rate. They managed to reduce the amount of data passed, keeping the rate of transmission prior to the bottleneck but presenting the original information at the destination. It is a statistical method of compressing information so it can pass through a bottleneck without losing its meaning and relevance. Their method solves the problem of finding the shortcode X that will preserve the maximum information about Y (Tishby, Pereira, & Bialek, 2000).

For this project of mitigating disruption in distribution facilities during phased upgrades caused by information constraint, ‘bottleneck’ is understood not how to get information at an acceptable rate from point a to point b, but how to find it at an acceptable rate. The time it takes to find information is what slows a project progression. The bottleneck is the problem of finding the needle in a haystack in a timely fashion.

CHAPTER 2

TASK OF COLLECTING INFORMATION

2.1. The Task of Collecting Information

In order to reduce the haystack where the information needed resides can only be achieved through targeted information collection with the understanding of the specific system one is dealing with. The understanding is achieved by collecting information on the general functionality of the system. This information can only be created by targeting the required data to provide the needed information that will be the bases for decision making (Goldratt E. M., 1990). The sum of information collected creates the knowledge of the general parameters and inner workings of the system since knowledge is understanding the meaning of how it truly functions (Zins, 2007). Once this understanding is established, one can dig deeper for information in the areas that have or potentially have a connection to the upcoming upgrade. The collection of this information is achieved by researching the existing explicit information and by tacit information gathering from the various stakeholders.

That means not to limit oneself to certain stakeholders limited only to the production facility but to expand it to include departments such as the customer's IT department but also their organization's headquarters. Their organizational chart must be well understood. From it, one has to categorize stakeholders according to their importance versus influence and affect versus affected (Grimble & Wellard, 1997). Stakeholders affect the progress of an upgrade and are capable of potentially derailing the outcome if neglected.

It has been learned the hard way that the most important member of the customer's team, such as the head of the IT department, is not the most influential person. It is the person responsible for the cybersecurity within the IT department that is the most influential. If that person is not involved in the project and deems that the changes to the information network caused by the project could have a potential risk to the IT system, that person will shut down the operation, and nobody will raise a question. Not even his or her direct manager or anyone in the organization. The perceived risks are too high.

In order to prevent situations like the one mentioned above, members of both teams need to develop a certain relationship that facilitates the transfer of relevant information that becomes knowledge. Morten T. Hansen of Harvard University states that a strong tie will constrain search, whereas a weak tie will hamper the transfer of complex knowledge (Hansen, 1999). In the case of phased upgrades of distribution centers, strong ties will help in obtaining the complex knowledge of which stakeholders who would be most of the beneficiaries in contributing the necessary knowledge are needed to execute the project successfully. One must consider the stakeholder concerns and demands and their wide range of diversity and take a multi-perspective approach towards them (Cook & Ferris, 2007). This is imperative to ensure the quality of this information and the rate of its transmission to the implementation team. This rate of transmission also depends on the type of information. There is a portion of it that is tacit information that resides with individuals and has to be extracted from them. These individuals that run the system are aware of the information and take it for granted, which creates a challenge in the performance of a subsystem upgrade. This tacit information is quite often not transferred to the individuals performing the upgrade. The most pressing challenge is how to get and gather information on the actual status of the system and turn the tacit knowledge into explicit. This converted explicit knowledge must be integrated into the existing one. It is the base of the overall knowledge needed (Liu, Chen, & Tsai, 2005). The challenge is not limited in finding the actual technical status of the system, but also on how the actual workflow of the distribution center is. It is an important factor that must be incorporated into the planning of the upgrade activity. It is to be understood that the knowledge being sought after is interdependent to other sub-systems. Since the knowledge being transferred is a combination of tacit and explicit knowledge, the importance of the relationship between the knowledge seekers and the individuals in the customer team having the knowledge is very strong. Their strong tie is imperative for the transfer (Hansen, 1999) and helps it in not becoming the main point of constraint in a system that sets the overall pace of the project progression (E. Betterton & CoxIII, 2009)

2.2. Information Collection is an Iterative Process

Establishing that the strong ties enhance the continuous flow of explicit and tacit information from the distribution center to the team performing the upgrade is the key in integrating all the technical disciplines that are involved in the upgrade project. Information collection is time-consuming, and it is difficult to judge if the information collected in a certain period is adequate. Information is collected and processed, and the result of each iteration leads to realizing further required information. The more information is collected and analyzed, the more it becomes evident that there are gaps in the information to have the full knowledge needed. These gaps help in narrowing the search field since they cover more defined areas. With each of these iterations, the gaps become narrower and the search areas as well, until the gaps narrow enough that the missing information can be deduced, and the design process can commence. This does not mean that the search for information stops, but it continues in parallel with the tasks. This resource is vital to ensure the quality of work. It cannot go indefinitely, as time is limited since it is set by the agreements with the distribution center on when the upgrade project will end. The vital critical information must be in place in a timely manner in line with the project plan.

2.3. The Forms of Information

Each task in a project needs information to be collected and processed as it is the bases of implementation of the various sub-tasks. The collected information is the input to the information processing, and its output becomes the input to the various tasks downstream from it. The information collection function is multi-faceted. It incorporates:

- Identification of stakeholders
- Understanding the function of each stakeholder
- finding out the expectations of each stakeholder
- Comparing technical documents against the actual state of the system
- Finding out the physical state of the system
- Taking field measurements
- Recording the customer’s workflow

All these facets help in understanding on how both parties are going to work with each other in implementing the upgrade and what their interpretation of the end goal is. It also ensures that the project implementation is in sync with the design. The information processing takes all this information and publishes it according to the functionality of the different teams performing the various tasks. Their output becomes the input to these teams and their tasks. It is a resource the same as any other physical resource utilized in a project (Zhang, Song, & Díaz, 2016).

2.4. Treatment of Information as a "Physical" Resource

Information should be treated in a project the same as any other physical resource. The issue one faces that information is not easily quantifiable. The more one searches, the more is revealed about the system in question. This uncertainty of quantifying this resource, is not considered, can put a project in jeopardy. If the project lacks this vital resource called information, it can be easily derailed by making decisions based on the perceived right information. Once it is realized that the correct information is not on hand, then the struggle to find it starts. This usually results in jeopardizing the projects' timeline, as finding the appropriate information is labor and time consuming, and the project is on hold until it is found.

The derailment of a project due to the lack of information can be avoided if information search and processing is considered a task the same as installing a piece of equipment. Information search is the same as searching for a specific sensor with certain specifications. The result is the procurement and installation of the sensor. The result of information processing is information on which decisions are based. Information gathering depends on finding the right stakeholders and verifying its validity. This process is time-consuming, and like any resource that is difficult to obtain, it quite often becomes the bottleneck that constraints the progression of a project. How such a constraint is controlled for it not to affect a project negatively, one has to deal with it the same as a physical resource constraint.

CHAPTER 3

THEORY OF CONSTRAINTS (TOC) & DRUM-BUFFER-ROPE

3.1. Theory of Constraints (ToC) & Drum-Buffer-Rope (DBR)

A method has been developed to deal with resource constraints and achieve a positive outcome. This method of how to deal with resource constraints was introduced in the Theory of Constraints (ToC) developed by Dr. Eliyahu M. Goldratt as a management philosophy. This philosophy was introduced in his book 'The Goal' that was published in 1984 (Goldratt & Cox, The Goal, 2014). Later the philosophy was adapted to project management in his book 'The Critical Chain,' published in 1997 (Goldratt E. M., Critical Chain, 1997). It explains how to deal with tasks that are constraints in relation to the other unconstrained tasks by using the Drum-Buffer-Rope method. In its traditional application in production systems, the constraint of the systems is the drum that dictates the speed or beat of production, hence the metaphor of a drum. The buffer pertains to the material reserves being fed into the constraint task so it can always perform optimally and not run any time out of material so as not to exacerbate the situation. The rope pertains to the feedback where the unconstraint processes downstream are requesting more material but are forced to produce at the pace the drum is giving, as illustrated in Exhibit 2. DBR aims to make the weakest link perform to its optimal capacity and prevent wasting valuable resources waiting for the output of the constrain. The prevention of resource waste and letting the system function to its true capacity enables the elevation of the constraint and finding a solution to improving its performance. Improving its performance, improves the system as a whole, as the drum will beat faster. The idea is illustrated in exhibit 2 below.

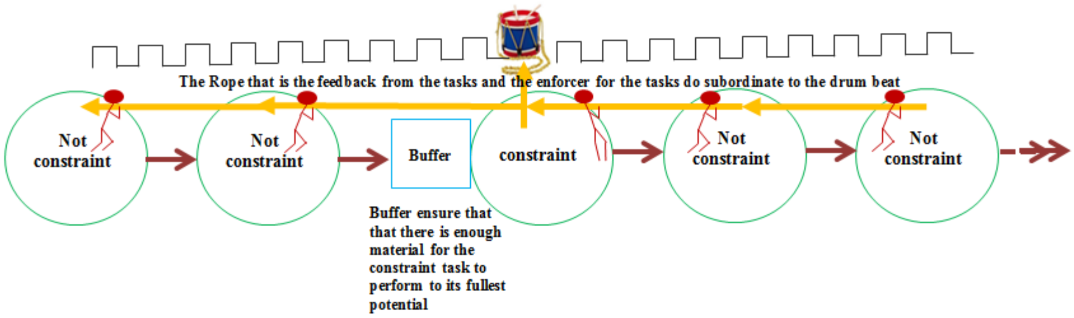

Exhibit 2 The Drum-Buffer-Rope

How does this fit in dealing with information? It can only fit if, as previously stated, information is viewed as a physical resource, the same as parts of an assembly and not viewing a bottleneck in the system through the lenses of 'Information Theory,' but through the lenses of DBR. The difference is clarified in Table 1. It shows why there is a difference in solving the issue of a bottleneck in the different spheres.

Information Bottleneck in Information Theory	**Information Bottleneck in TOC**
The information is known	The information is an unknown entity
The bottleneck is a transmission constraint	The bottleneck is an obtainability constraint
Information compression is the solution	Treatment of information as a physical source is the solution

Table 1 The Different Treatment of Bottlenecks in Information Theory and TOC

Before considering ToC, Concurrent Engineering has been considered. It takes into consideration the demands, concerns, and a multi-perspective approach towards the stakeholders considering their wide range of diversity (Cook & Ferris, 2007). In short, it concentrates on the information presented by all stakeholders. The collected information makes all parties participate and function as a system within the environment in which the project evolves, since all do not exist in a vacuum (Katina, Keating, & Jaradat, 2014). Procedure and clear paths are set based on the information to minimize the risk by ensuring that it is available to all participants. It makes knowledge management a contributor to risk mitigation (Haltiwanger, Pinto, Landaeta, & Tolk, 2010). Concurrent engineering plays a significant role in project development, and information between all engineering disciplines, management, and the stakeholders in the market is the catalyst that keeps all the parallel threads working in sync. Any change done in one of the threads without informing the others has a forwards and backwards effect on all of them. These backwards and forwards effects or chaining are used in the planning process (Nategh, 2009). Analyzing these effects in their totality gives the planner the vector where the teams must set the focal points in the process. It also indicates the sensitivity of the different processes as they relate to the project in a rating scheme. The forwards and backwards effect shows the teams how their work will affect each other's work and to which degree (Nategh, 2009).

Another way of keeping the concurrent running threads on track is by using the methodology Matrix of Functions and Functionalities (Zadnik, Starbek, & Duhovnik, 2012). It emphasizes the functional requirement to keep the teams of different disciplines focused as they will fail to work in unison without a transparent system in place. Matrix of Functions and Functionalities helps in defining the technical systems that are needed in each functional requirement. Once each functional requirement is assigned to the relevant technical systems, they can be sorted according to relevance showing the interrelationship between the different ones (Zadnik, Starbek, & Duhovnik, 2012). This methodology is not the only one, but the teams within these threads constantly communicate with each other to stay on course. These teams are not teams in the classical sense, with a well-defined top-down structure. They are cooperative teams that have dynamic leadership. The main job of the leadership is the job of a facilitator (Prasad, 1996), who makes sure that no one person dominates to further their idea, but that the ideas are based on scientific and engineering bases. It is also essential to make sure that information goes from the bottom up, from the production floor back to the development team. A rigid sequential process, in this case, would not help, making information flow through a gate to the rest of the team is the solution (Sommer, Dukovska-Popovska, & Steger-Jensen, 2014).

Concurrent engineering, which is also known as simultaneous engineering and integrated product development, is looked at by many as the solution and a great process in product development. Many papers were written on this subject matter probing and finding ways on how to improve it. It is evident from the article written by Rob Dekkers, C.M. Cheng, and Jochem Kreutzfeldt reviewing articles in this field (Dekkers, Chang, & Kreutzfeldt, 2013).

The weakness of concurrent engineering is its reliance on a high degree of certainty. It is based on good reliable information with a low degree of unknowns. It does not have the mechanism of dealing with a fluid environment but is more adapted to an environment with slow changes that fit within a system. In an environment that requires quick adaptation to ever-changing circumstances, it is ill-suited.

ToC, on the other hand, is a system that is dedicated to how to deal with a very fluid environment. It has a mechanism of adapting to the ever-changing environment due to unknowns. This mechanism is known as POOGI that pries and probes in order to find the constraints that could doom a project. ToC is the foundation of the current methodology that is a road map ensuring the phased upgrade to perform with the highest possible throughput without wasting resources unnecessarily.

3.2. Using Drum-Buffer-Rope (DBR) to Find Solution to Constrained Operation

The method of dealing with constraints and improving the system by following the ‘driving on-going improvement’ recommended by the theory of constraint (ToC) (Goldratt & Cox, The Goal, 2014). They are the five focusing steps known as POOGI, which stands for **P**rocess **O**f **O**n-**G**oing **I**mprovement (Watson, Blackstone, & Gardiner, 2007), (Goldratt & Cox, The Goal, 2014). These steps are:

1. **Identify the constraint**

   In a production line, a cell is running as fast as it can but is not fast enough in producing the subassemblies needed for the next steps in production. It is imperative to identify that cell and acknowledge that it is the constraint.

   In project implementation, how to accomplish the physical task is clear, and there are no issues with the technical understanding of how to do it and how fast it can be achieved.

If the implementation takes place with total disregard for the environment it functions in, which is the facility's operation, the outcome is a catastrophe for the facility. The issue is how to integrate the upgrade without jeopardizing the throughput of the facility. The constraint is the information that must be collected, processed, and integrated into the project plan. It is holding up the physical tasks downstream since the information needed is often not acquired on time. In return, the project conflicts with the facility's operation, and it slows down the progression of the project.

2. **Exploit the constraint**

In production planning, if a production cell is the one that is holding up the processes downstream, then one makes sure that it is supplied with all the needed material in a timely fashion. One builds a buffer of material for it to draw from. This is done to ensure that it is running at its optimal capacity and is not the cause of further unnecessary delays.

In our case, the finding and processing of the information needed to establish the right optimal workflow is the "cell" that is the constraint. It is done to ensure that the physical tasks downstream commence as planned and are not further constrained; the proper resources must be deployed. These resources have to make sure the relevant information (e.g., raw material) reaches its targeted audience expeditiously and even builds an information buffer. It is imperative for them to function optimally in order to exploit the constraint to its maximum capability.

3. **Subordinate to the constraint**

In production, many cells downstream from the constrained cell perform faster and often sit idle until they receive further material. This means that the facilities pay workers to sit idle, waiting to be able to commence with their work once the appropriate material is received. To prevent this from happening, the planning of the workflow must subordinate to the constrained cell. This means deploying just enough resources, so the faster cells function at the same speed as the constrained cell. By adapting the workflow to the constrained cell, waste is prevented.

The same philosophy is applied. The downstream tasks performance is adapted to the rate of the information received. Tasks that are not planned based on information should not be performed since they will be performing in a void, causing chaos to the facility's workflow. They would have to cease functioning to prevent any negative impact, resulting in idle resources and waist. They have to perform at the rate according to the information received.

4. **Elevate the constraint**

In production planning, realizing that a cell in the production line is the constraint that is holding up the entire line, one tries to find solutions to elevate the constraint. This is typically done by adding resources, buying new faster equipment, creating a parallel cell, or any other method in order to increase the production speed. Once the known constraint is elevated, the whole production line will increase its production since its performance relies on the constraint cell.

Obtaining the relevant information (e.g., raw material) at an acceptable rate is the goal that must be strived for. It can be achieved by having the right resources performing the job. Once the right resources are in place, and they can perform optimally, the tasks downstream will increase their performance.

5. **Prevent inertia from becoming the constraint**

This last step is essential in the solution to the dilemma of facing constraints. Once a constraint is elevated and the tasks downstream perform faster, one tends to make them all run at their maximum capacity. Suddenly other constraints pop up, which in return cause idle resources. As was mentioned, idle resources are waste that has negative economic impacts. One must speed up the production line slowly to find out what the new true production capacity is depending on new constrains that manifest themselves. Once the problem of getting the raw material called information at a higher rate has been achieved, one thinks the issue has been resolved. The tendency is to speed up the project, but suddenly one experiences that tasks start performing out of sequence because other tasks downstream need a different type of information that is not obtained fast enough. That is the reason why the tasks are sped up slowly and at each step going back to step 1. Step one is identifying the new constraints that pop up, and the project must be adapted to the new reality. The process is illustrated in Exhibit 3 below.

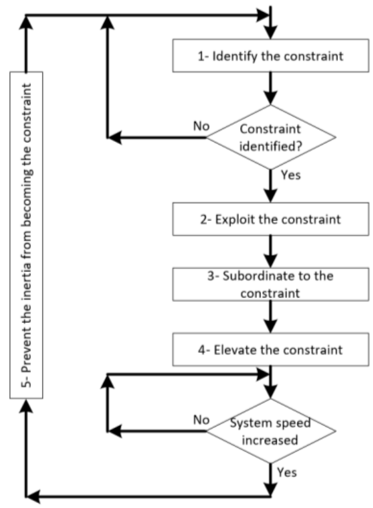

Exhibit 3 POOGI

3.3. Five Focusing Steps of POOGI

The five steps above reveal that a project can never go faster than the pace of the dominant constraint task within it. Similarly, production throughput cannot produce faster than the constraint process within the system. ToC came up with a solution on how to manage and exploit this. DBR explains how to adapt to the existing constraint and improve upon it without wasting resources. POOGI, in return, explains the mechanism on how to identify and focus on solutions to improve the overall performance of a project. Once the necessary information is found and a constraint is elevated, another task or multiple of them in the project can suddenly become constraints as they now become the bottleneck. The fifth step in POOGI warns that one must stay vigilant and speed up the project stepwise continuously repeat the focusing points to stay ahead and elevate and adapt to the new arising constraints using DBR. These constraints are not new, as they always existed in the system but were performing better than the existing dominant constraint. Once the existing dominant constraint has been elevated, the next slow task manifests itself as the weakest link, and it must be dealt with. All other tasks have to subordinate to the new constraint. It is now dictating the drumbeat to which all tasks must march. Now the drum beats slightly faster according to the new constraint that has manifested itself. In order to elevate the constraint and keep it functioning at its optimal pace, enough information has to be supplied for it to process without interruption. In production, it means to have enough material to build a buffer so that the constraint can be fully utilized and not cause any further delays since it has a buffer of the needed material. In our case, the material is information, and enough of it is to be collected to build a buffer to keep processing it for the tasks in the project that need it. The more information is found, the more one starts elevating the information constraints. It depends on finding the right pertinent information, which depends on many factors. Such as how up to date the explicit information is, how quickly all the tacit information can be collected, how good the relationship between the information seekers and the information owner are, how fast the relevant stakeholders can be identified, and so on. It is important to realize, if all tasks in a project do not progress to the rhythm of the drumbeat, then many will come to a stop. They will wait for the constraint task to catch up. This would result in idle resources, and such waste will put an economic strain on any project.

The starting point to find the required information is based on the Scope of Work (SOW) agreed upon between the party requesting the upgrade and the ones performing it. It is a top-level agreement on what the end goal of the job will achieve, such as, for example, the change of certain equipment to achieve a certain desired throughput. The SOW defines the main objective of the project limited only to the technical aspects of what the end goal should be, but not how it is to be achieved. It defines the equipment (hardware) and any related software upgrades. This becomes the starting point or nucleus information on which further information will be gathered to design and develop the methodology on how to perform the upgrade without impacting the daily activity of the distribution center negatively. The information collected has to be managed and filtered on what is relevant to the upgrade project and what is irrelevant. It is essential to distinguish between meaningful information and irrelevant information. Which information is relevant, and which is not, can only be judged by understanding the categories of issues that will be faced during the execution of the project? These categories are mainly technical, process, and organizational. They are codependent and affect each other. This makes the information gathering the main challenge – the drum - to keep the rhythm of the drum at an acceptable pace, and it is only possible by establishing a good information buffer, as the tasks downstream will demand more information in order to try to progress faster by tugging at the rope. The rope is the system feedback for more material (i.e., information), and it is also the rope that holds them back for them to march according to the drumbeat, as illustrated in Exhibit 4.

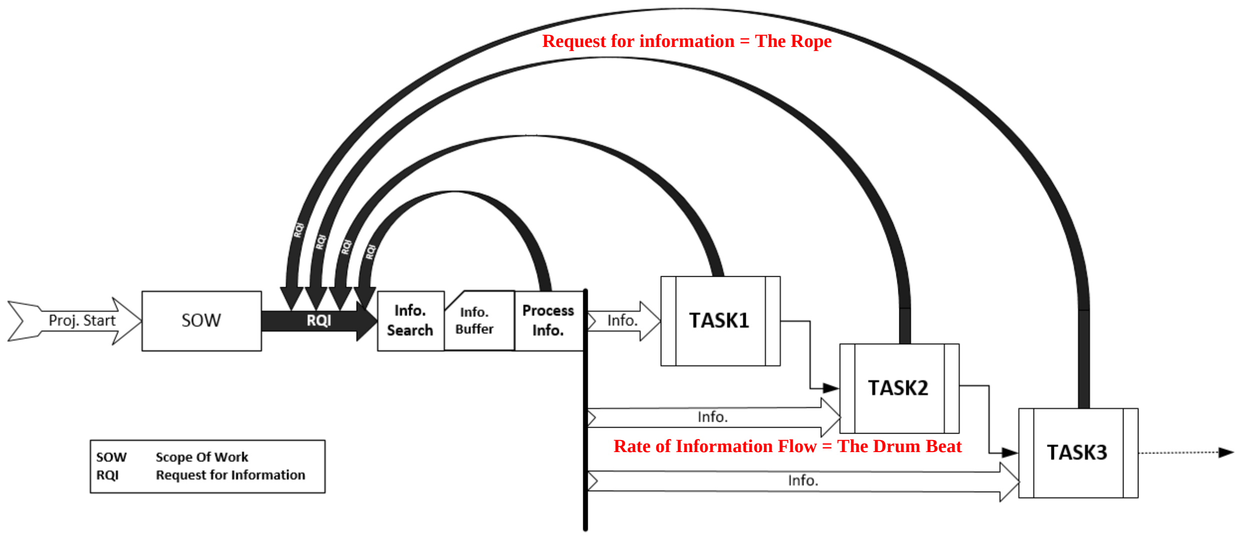

Exhibit 4 Traditional DBR and DBR as applied to phased upgrade

3.4. Importance of information in a Project

Project success is due to a good information connection between the company performing the upgrade and the customer. If a project fails, it is due to information not being appropriately passed through the various channels. That means stakeholders are not receiving the proper information, or others are not asked the right questions to obtain the relevant information. This results in an information disconnect. The information disconnect impacts the economic health of the company. It also impacts the customer in the form of a reduction in productivity or even a work stoppage. The resulting economic damage to the company and the customer is listed in table 2 below.

Economic Damage caused by Information Disconnect			
The Company		The Customer	
1	Schedule delays	1	Reduction in productivity due to production line limited availability.
2	Resource conflict with other projects	2	Production suspension due to production line unavailability.
3	Idle resources causing a financial drain	3	Furlough workers due to the production slowdown
4	Budget overruns	4	Not providing an adequate volume of products to their points of sale.
5	Project result discrepancies (failure of customer expectations)	5	Potential market erosion or loss.
6	Liquidating damages due to delays		

Table 2 Economic Damage caused by Information Disconnect

3.5. DBR synchronizes resource flow with task progression

DBR is a method that synchronizes the progression of tasks with the inflow of resources, and in our case, the resource is information. If any resource is missing, then how can the tasks on hand be completed? A task can progress within a project, as long as the proper resources are available. If information, a vital resource, is on hand, then task planning, system designing, etc. can progress based on it. That is the reason why work to be performed can progress most efficiently if the task performance is in sync with the resource inflow; whichever form it is in. Resources can come, for example, in the form of human, material, or the most neglected resource: information. The inadequate supply of any resource, even information, will cause any project to be negatively impacted. DBR is a tool that helps mitigate against risks of project failures by ensuring the harmonious coordination between resource flow and task performance. This is only possible if all needed resources are adequately identified. The failure of forgetting a resource, such as information, increases the risk of potential failure exponentially.

CHAPTER 4.

METHODOLOGY IN DEALING WITH INFORMATION AS A PHYSICAL RESOURCE

4.1 Methodology in dealing with Information as a Physical Resource

How can one prevent project failure due to the lack of resources called information? This is an issue that is difficult to solve since information as a resource is not easy to quantify. In order to deal with information as a physical resource, a methodology has to be followed that will help to quantify it into a manageable entity. A method that will go step by step building first a foundation on which an iterative process helps with dealing with the fluidity of the projects. The method, represented in the ten steps listed below, enables proper definition and quantification of the information needed. It would keep a project on even keel and ensure synchronization of the resources with the tasks performed in a project. These steps are:

1. Treat information the same as a physical resource.
2. Plan information gathering and processing tasks as part of the project the same as a physical task.
3. Assign adequate human resources in obtaining information and processing it.
4. Define what information is needed.
5. Identify all stakeholders.
6. Collect and process as much relevant information as possible.
7. Continuously plan or adapt the project based on the information found.
8. Incorporate and/or adapt the project into the customer’s workflow.

9. Use the DBR methodology to ensure the project tasks progression is in sync with the incoming resources.
10. If the project is still not finished, go back to step 4, as the process is iterative.

How to use these steps is shown in exhibit 5. First, one ensures that the conditions stated in steps 1 through 3 are fulfilled. They are the foundation on which any project planning and execution are based. Steps 4 through 10 are iterative, and they are there to ensure that adequate information continuously flows to the tasks on hand. This gives the capability of ensuring the possibility to adapt any project to the dynamic nature of the system it lives in. Using DBR in step 9 is there to make sure that the project is progressing to the rate of the usable information received, which is a scarce resource. It is scarce since it depends on many sources that are not always easily identifiable.

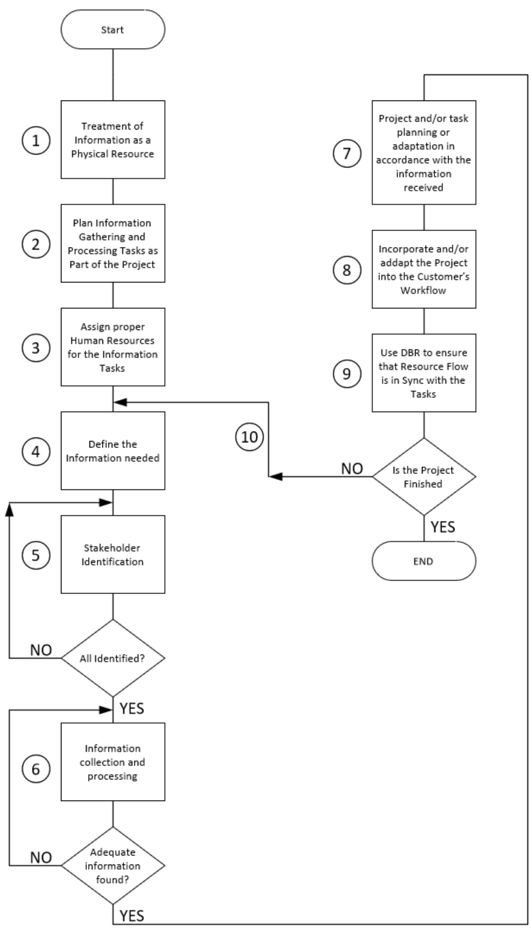

Exhibit 5 The Steps to Apply DBR to Phased Upgrade

The cases below demonstrate the importance of following the above-stated procedure. It will show the importance of the vital resource identified as information and the importance of making sure there is no disconnect between the company and the customer.

4.2. Case 1: Upgrading the Monorail System

A multi-level distribution center receives merchandise on pallets from trucks onto the receiving dock. The pallets are inducted by being placed onto the induct conveyors. They are transported via these conveyors to elevators that bring them to the transportation level, where they are picked up by trollies. These trollies, which are a mono-rail system, transport them to the inducts of the cranes, also known as SRMs (Storage and Retrieval Machines). The SRMs place the pallets into their designated racks. This monorail system has been running for the last fifteen years without any significant upgrade, and its control system has become obsolete. The owners of the facility would like to upgrade the system to the latest technology without impacting the operational target of the facility and placed the following restrictions:

- The upgrade activity can only take place when the facility is not inducting merchandise.
- The throughput of the trolley system must be maintained in order not to impact the productivity of the facility.

In order to upgrade the monorail system, the following upgrades must be performed under the stated conditions. These upgrades are:

- Upgrading the communication system between the base and the trolley system to a Wi-Fi system
- Upgrading the control panel of each of the 30 trollies to upgrade the control system
- Upgrading the positioning system to an absolute positioning system.

In order to plan that project, the team needs reliable information in order to integrate their activity with the daily activity of the facility. They started by focusing on the first three steps of the stated methodology.

1. Considering information to be a physical resource being given the same attention as other resources, such as human resources, design activity, hardware sourcing, etc.
2. Planning the project, the team allocated specific tasks within the project for information collection and processing. These tasks will be providing information for the continuous adaptation of the project to the ever-changing landscape of the system it will reside in.
3. Making sure the information gathering tasks are not understaffed. They assigned the proper human resources that are capable of performing such tasks.

   Following the first three steps has laid a solid foundation to start with the iterative portion of the methodology. This portion enables the project to adapt to the changing operational landscape constantly, and it begins by following the steps of the methodology.

4. Define the information needed
   a. What activity can be performed without disrupting the customer's throughput
      i. When can it be performed?
      ii. How can it be performed?
      iii. How can it be later integrated into the downstream activities?
   b. What activity will disrupt the customer's throughput
      i. When can it be performed?
      ii. How can it be performed?

iii. Can it be performed in the allotted time slots?

iv. If it can't be performed within the allotted time slots, what is the level of disruption?

v. If the upgrade will cause a level of disruption, how can it be coordinated with the customer so it would have no or minimal ill-effects on their business?

5. Stakeholder identification

Further, the stakeholders that have the decision-making authority must be identified. This activity is not limited to the customer's stakeholders but also to internal stakeholders. There are decisions to be made on how to proceed with the design and implementation, depending on the stakeholders.

The most important stakeholders that have been found at the customer's side that gave the team vital information after going through several iterations are:

a. Team leaders managing the daily product induction activity on the loading dock.

b. Operation managers.

6. Once the customer's and internal stakeholders have been identified, and the information collection and processing commenced, it resulted in the following information:

a. Information from internal stakeholders

i. Upgraded and not upgraded trollies cannot run simultaneously.

ii. The facility would have, for a certain amount of time, to meet its target with only 50% of the trollies operating.

iii. The installation of the new positioning system will not be a disruptive operation.

iv. The installation of the Wi-Fi system will also not be disruptive.

b. From the customer's stakeholders, the following information was obtained:

i. There are periods of reduced market demand after the holiday season.

ii. During such a period, it was agreed that the customer would send more merchandise to its stores to cover the period of low induction.

iii. The customers will coordinate with its suppliers the delivery of goods during the period of slow induction.

iv. It has been found that the facility is meeting its demands with 80% capacity of the monorail system, as five trollies are not being used due to various technical issues.

7. By using the information collected, the project plan was adapted to the circumstances it will operate in by:

a. Installing the positioning system and the Wi-Fi as the first step without disrupting the customer's operation.

b. Upgrading the five trollies that are not being used due to technical issues will also not disrupt the customer's operation.

c. The following plan was presented to the customer:

i. There is a total of 30 trollies, of which five are already upgraded.

ii. It is possible to upgrade five trollies daily.

iii. Induction would have to be ramped down gradually to a point and ramped up again, as every day, five trollies will be withdrawn from the system to a certain point then reintroduced.

iv. The implementation will follow the schedule below:

- Day one, the five nonfunctional trollies, will be refurbished and ready to be used with the new upgrades.
- Day two, five trollies are withdrawn to be refurbished, and at the beginning of the shift, 20 trollies will stay operational.
- Day three, five trollies are withdrawn to be refurbished, and at the beginning of the shift 15 trollies will stay operational
- Day four, all 15 operational trollies are swapped with 15 refurbished ones.
- Day five, five refurbished trollies are introduced into the system, increasing the operational trollies to 20 trollies.
- Day six, five additional refurbished trollies are introduced, increasing the operational trollies to 25, which puts the system back to the previous capacity prior to the upgrade.
- Day seven, the last five refurbished trollies are introduced to the system, increasing the count of operational trollies to 30 trollies. This increased the capacity by five trollies in comparison to prior to the upgrade.

8. In order to incorporate the upgrade workflow into the customer's daily operation was only possible with some temporary changes, the customer had to do to their workflow. With the agreed-upon changes, the customer coordinated with their stores and vendors a temporary change in product flow. This made it also possible to adapt their resources to the temporary change in workflow. Both have reached a situation of minimal disruption without putting their respective operation in jeopardy.
9. With securing the information flow, the project was executed according to the presented plan and adhering to the DBR methodology. The project morphed into the workflow of the customer, and by following the restrains that DBR imposes, as explained below, the project flowed in sync with the information flow and the customer's process.

The Drum

The information gathered established the fact that the part of the project to refurbish the trollies had to be delayed to the time of low market demand, which is after the holidays. It also made it in the meantime possible to identify the stakeholders to negotiate on how to proceed. This time-consuming process of gathering the information and the resulting plan set the drumbeat on how fast the project is capable of progressing in order not to waste resources and be successful.

The Buffer

The gradual buildup of the repository of information creates a buffer for the needed information to accomplish the various tasks. Tasks such as finding out if the distribution center functions optimal.

This recognition and elevation of the constraint led to the coordinated plan to increase deliveries before the beginning of refurbishing the trollies to compensate for the four days of reduced capacity. The capacity was reduced to an average of 70%, but by the seventh day the facility had 30 trollies running in the system. This is an increase of 20% capacity in comparison to the period prior to the upgrade. The search on how to elevate any dominant constraint must be pursued in order to increase the frequency of the drumbeat. It is done by identifying the reason why the constraint exists and take the appropriate measures. It will never be totally elevated-but will fall in line with the desired rate of progression.

The Rope

The rope is the conduit of resources, in our case information, to the tasks downstream. The tasks downstream constantly pull at the rope send their requests back for more material and resources so they can finish their tasks as expeditious as possible. The system can only provide these tasks with what is available. The pull at the rope is the request for more input (in our case information), but at the same time, the rope restricts the tasks from advancing faster than the other slower moving tasks. All tasks have to move forwards in sync.

This is the reason why the restrain DBR imposes, making sure that the project progresses in accordance with the resource flow. There was a tendency of trying to withdraw more than five trollies (surge ahead) to hasten the upgrade. This would have impacted the customer's induction operation, as they were planed according to the capacity of the trolley system performance. This would have upset the customer's workflow. The tendency to surge forwards would have caused the two workflows to go out of sync and to cause a reduction of inducting capacity. Such a reduction meant the customer would have an overcapacity in the workforce during that shift and not being able to handle the quantity of the incoming merchandise. In return, the customer will have to catch up and increase the induction time, which will impact the workflow of the company performing the upgrade. Basically, one thing will lead to the other, and both parties' workflow will suffer as it is not anymore in sync, and they will incur economic losses.

10. The process went through several iterations to find the right stakeholders, and the information found and processed influenced the project planning and the interaction with the customer continuously until both parties agreed on how it is going to be executed. Each time step 10 was reached, the process jumped to step 4 until the project ended.

The implementation of the project, in this case, showed the importance of integrating it into the customer's operational system. It is only possible by identifying the right stakeholders and acquiring them the relevant information. Not having the correct information on which all decisions were made on how to proceed without disrupting and impacting the customer's operation negatively. The achievement was of the balance between the facilities targeted daily throughput with the project progress. It was planned with the customer on how to handle the temporary reduction of throughput, and the strict adherence to it. It has to be accomplished without succumbing to the urge of wanting to accomplish more then what was planned. Controlling this urge, also known in DBR as the surge, is key to success. The key to success is not only controlling the surge, but in the integration of the project tasks into the customer's workflow. Succumbing to the surge of moving faster, not based on good information, creates problems that will impact projects negatively is demonstrated in the next case.

4.3. Case 2: Automated Tray Building System

A customer contracted to install an automated tray building system. The tray building system would take a layer from a pallet and placing it on a tray. Each layer measures a maximum of 44" X 52". The trays, on the other hand, have the same dimensions as a standard pallet, which is "40 X 48", but contrary to the pallets, they have a height of 1.5" instead of 5.5" height. These trays are also used as pallet support boards in case a pallet's underside is damaged, by placing a pallet on a tray. This helps in transporting damaged pallets without causing issues during transportation through the system and not having to place the product on another good pallet.

The contract was signed to install a robotic system and integrate it into the existing automated distribution center. It was installed successfully. It picked the layers and deposited them as designed on the trays. Once the trays were built (had a layer deposited on them), they were conveyed to the SRMs (Storage and Retrieval Machines) to be deposited to their designated slots. At this point, many of the SRMs went into a fault mode once the tray was transported unto their load handling unit. The error displayed was an overhang condition.

An overhang condition means that the product is not properly positioned, violating the envelope it should be in. If it is not within that envelop, there is the potential danger of colliding with other products in the racking system or even with the rack while the SRM is moving up and down the aisle to reach the designated rack location. Such a collision would cause serious equipment damage and delays

So, what went wrong? It seemed the project went smoothly during the implementation, as there were no complaints. The problem is not during implementation, but during the actual sales phase of the project. Traditionally sales effort is not looked upon as part of the overall project, especially technical sale, where an idea, improvement, or solution is presented to a customer. The sales process in these cases is not considered a part of the engineering process until a contract is signed. The engineering effort during the sales phase is kept to a minimum at best to keep the sales cost low. The sales process is also based on estimating the resources that will be needed when the time comes to implement what has been sold. It itself needs resources to perform an adequate job, and this resource is a certain amount of information. In that sales process, the resource called information was neglected and was not treated as a physical resource. Sales ignored the 10-step process and went directly to step 9 and neglected to:

1. Treat information like a physical resource. Sales concentrated on identifying all the hardware and software that is needed to perform the assigned tasks.
2. It neglected to plan information-gathering tasks within the sales process, the same as identifying the physical resources needed for implementation.

3. Adequate human resources were never assigned to dig and search for the necessary information.
4. The definition of the needed information never took place, as the proper infrastructure was never put in place
5. Since the definition of the required information did not take place, it was not possible to identify the appropriate stakeholders.
6. No adequate information was collected and processed.
7. The negligence of not following the previous steps continued in the implementation phase, and the project was never adapted to the reality in the field.
8. The project had minimal impact on the customer's workflow because it was a parallel process that enhanced the manual operation.
9. DBR was not followed in the sales phase, which by itself can be considered a project, that must follow like any other project the same processes. The sale was based on pure theoretical information, which was logical. The throughput numbers increase for the customer were very promising, and in the euphoria, the team and the customer surged forwards not wanting to slow the sales project. They presented an unfinished product, as certain hard to get resources were missing and were deemed of no consequence for the final result. They all missed the following vital information:
    i. All pallets and trays are squared at every transfer point by bumping against a stop.
    ii. The trays that are manually loaded do not have a product overhang

iii. The stops are 4” high and the 5.5” pallet bumps against them and not the overhanging product

iv. The trays do not have an overhanging product, so the 1.5” high tray bumps against the 4” stop when being squared and not the product.

v. If a 2” product overhang is bumped to square the load, it will shift the center of the load by 2” creating a 4” overhang on the opposite side.

10. If the project is not finished, go back to step 4 does not make any sense, since a vector in moving forwards has been chosen without looking back.

In order to remedy the situation, there are potentially three ways of solving this issue, and they are:

1. Change the bumps, for them to be 1” high
2. Change the trays to trays that have the same height as the pallets
3. Deposit the layer of products without having an overhang

All these three solutions have drawbacks that make them not feasible.

1. Changing the bumps is not feasible because:
    a. It is cost-prohibitive, as there are nearly a hundred throughout the system.
    b. Many pallets weigh up to 3,000lb, and the force of them being pushed against a 1” high stops would cause damage to the pallets from the pressure. It is also to be noted that many pallets have pieces missing at the edges and would not be positioned properly.

2. Changing the trays to the height of a pallet would not make any sense. The idea of putting the products on trays is to increase the rack density in the pick isles for these items.
3. Depositing a layer without an overhang is not possible due to:
    a. The end effector of the robot would have to be changed to make it possible to pick single cartons and deposit them on the tray.
    b. A whole layer would not fit on to the tray. Some cartons would be leftover.
    c. The throughput would be decreased substantially. Moving a layer from the pallet to the tray are two movements. One movement is picking the layer and depositing it onto the tray. The second movement is for the robot to go back to pick the next layer.

       If the robot is to pick individual cartons, then the movement per layer will increase by the number of cartons, and the transfer time per layer will multiply according to the number of cartons.

If one looks at this failure from the perspective of ToC and considers the DBR process, it will become obvious that the sales of this system expansion should have been considered and treated as a project. Sales mainly depend on the resource identified as information. The preliminary calculation showed that the tray building using a robot would increase the throughput to the satisfaction of the customer. This “positive” information caused the sales team to surge and were impatient to cope with the slow acquisition of more information. This caused key information, such as the product overhang in relation to the height of the bump, from never reaching the right stakeholders on time. The information flow as a constraint was never identified as the surge took over, and it became the constraint. It blocked further information from reaching the proper stakeholders. A step back was never taken to exercise the five focusing steps known as POOGI, which stands for **P**rocess **O**f **O**n-**G**oing **I**mprovement (Watson, Blackstone, & Gardiner, 2007), (Goldratt & Cox, The Goal, 2014), which were previously discussed. These focusing steps would have helped in engaging stakeholders to identify any missing information. Unfortunately, the surge choked off any further flow of information. The absence of this resource caused the failure.

This case draws the attention that one has also to gather the information that would have a negative impact on the project and find solutions. Not finding solutions is not an option; even sales must find a solution before a proposal is presented. That is why one other step must be added as a risk mitigation step. The added step would be the step between the previous steps 6 and 7, as shown below. Exhibit 6 shows the adapted flowchart of the steps.

1. Treat information, the same as a physical resource.
2. Plan information gathering and processing tasks as part of the project, the same as a physical task.
3. Assign adequate human resources in obtaining information and processing it.
4. Defining what information is needed.
5. Identify all stakeholders.
6. Collect and process as much relevant information as possible.
7. ***Find information resulting in a negative impact and find a solution.***
8. Plan or adapt the project based on the information found.

9. Incorporate and/or adapt the project into the customer's workflow.
10. Use the DBR methodology to ensure the project tasks progression is in sync with the incoming resources.
11. If the project is still not finished, go back to step 4, as the process is iterative.

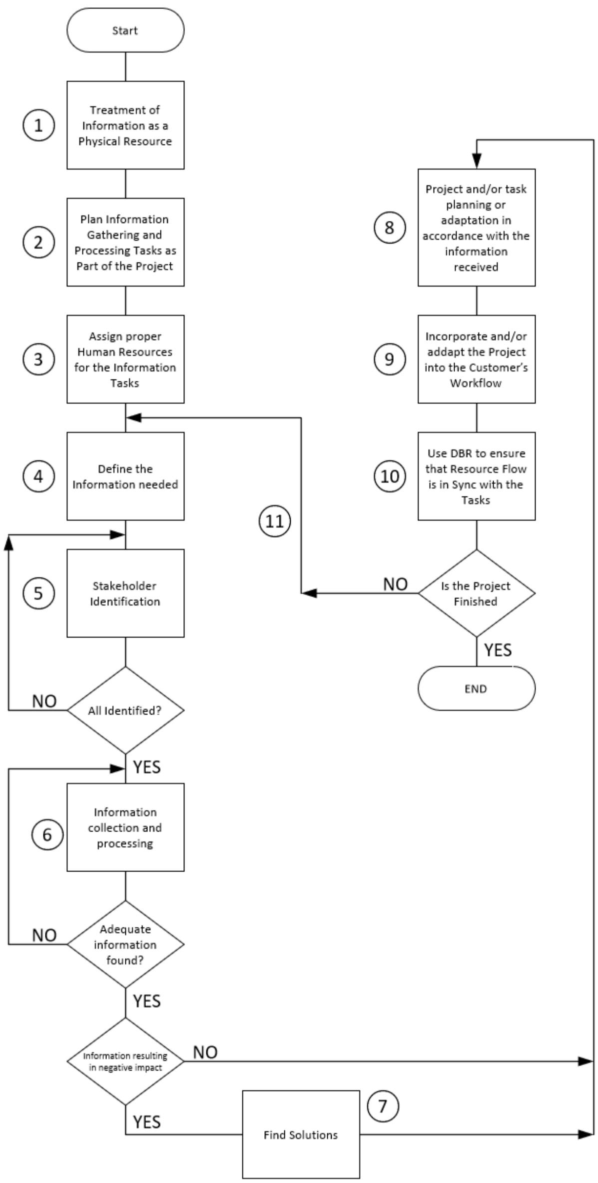

Exhibit 6 Revised Steps to Apply DBR to Phased Upgrade

In this case, the solution that was presented and sold to the customer was based on pure high-level throughput information. Information usually found in executive summaries where details are of no consequence, but in this case, it was of consequence. The salesforce based their concept on the high-level information and neglected the fact that the product layers on the pallets have a 2” overhang on each side. This oversight would have been prevented if all stakeholders were included. If the concept based on the high-level information had been presented to the right stakeholders, the issue with the 2” overhang would have been exposed and a different solution researched. Not finding information that could potentially derail a project can be detrimental. The next case shows that the team executing the project was confronted with information that had potentially a negative impact on the project. They found a solution in the simplification of the installation.

4.4. Case 3: Induct Conveyor System

The customer requested to upgrade their induct conveyors that were installed over ten years ago. This upgrade entails the replacement of the conveyors with new ones, the replacement of all sensors, and control electronics since most of them are rendered obsolete. It is becoming difficult to obtain the appropriate spare parts. Such an upgrade would have to take place in a multiphase fashion since the condition is not to impact the daily activity of the facility. The upgrade activity would take place every day in a twelve-hour window where no product induction takes place. The product induction starts at six in the morning and normally stops at six in the evening. During the project planning the new 11-step process was followed by:

1. Treating information, the same as a physical resource, by making an effort in acquiring it the same as a piece of equipment.
2. It was consciously put in place tasks to find information to understand the condition under which the project must be implemented.
3. In order to find the pertinent information, the proper human resources with appropriate experience were assigned with the task.
4. After visits to the project site, it has been established that the following information is needed:
   i. The induct daily schedule of the facility.
   ii. Is it a regular schedule, or are there daily changes to it?
   iii. What are the realistic working hours?
   iv. How is the condition of the control infrastructure?
   v. What changes in the design can reduce the work on-site?
5. In having these questions, the following stakeholders have been identified:
   i. The facility induct operation manager.
   ii. The various team leads on the induct dock.
   iii. Maintenance crew lead.
   iv. Various maintenance employees.
6. The information received from the various stakeholders it has been established that:
   i. Product induct takes place daily from 6:00 am to 6:00 pm.

ii. The system has a centralized control system where all sensors and motors go to a central cabinet. It has been decided to decentralize the control system to reduce the number of cables running back to the central control cabinet.

iii. The version of the software controlling the system has been established.

iv. It will be possible to install daily 3 new conveyors (10 hours for installation, 1 hour for software adaptations and 1 hour for verification).

7. It also has been found by searching for information that could negatively impact the project, that the induct operation quite often runs up to 8:00 pm, but always starts at 6:00 am sharp. That means, quite often, the installation time is reduced from 12 hours to 10 hours, but the system has to be ready to run at its nominal capacity every day at 6:00 am.

8. Having the information on hand that the working time would often be reduced to 10 hours, it has been decided to run the daily tasks accordingly. Only two conveyors will be replaced daily. This adaptation to the site reality was the only way to have both workflows in sync with each other.

9. The implementation of the upgrade commenced as planned in accordance with the resource flow and time restrictions. As the decision was made since the existing PLC (Programming Logical Controller) has the capability of supporting signal networking, it would reduce the field wiring drastically. The remaining wiring would be mostly using prefabricated pluggable cables. This solves the problem of running new signal input and output cables to the main control cabinet, and the existing cables can be gradually decommissioned for later removal. It also reduces the commissioning time

in the field, since the various localized control panels have been tested before sending them to the site, where they will be connected via the input and output network with the central control cabinet. This puts the burden on the control software programmer that adapts the software to the new hardware simultaneously while the hardware changes are made. At the end of each day, the new conveyors worked with the old as a system.

10. It was important to follow the DBR process and have the workflow be in sync with the installation resources in not acceding the facility start-up time of 6:00 am each day. It is crucial not to let the surge take over and try to install more conveyors then planned and stay in sync with the workflow of the facility.
11. Every day the stakeholders were contacted to make sure if there are any changes to the existing information. This is done by going back to step 4.

Not impacting the product induction operation of the facility negatively was the goal, and it has been achieved. It has been achieved by not letting the inertia or surge take over. That would have meant that the facility would have had to wait until the installation phase would have ended much later than promised. This situation would have disrupted the workflow of the facility resulting in an idle workforce waiting to unload the trucks and trucks being delayed from returning to pick other loads. Such a delay has negative repercussions throughout the system. That is why the information exchange with the right stakeholders and adapting according to the dynamic daily workflow changes is essential. Further, the quality of information is essential. Like any resource, the quality of the resource dictates the outcome. They managed to work with the customer in synchronizing the workflow around the irregular hand over time of the system. They managed to plan and adapt their activity accordingly and not let the surge take over.

4.5. Case 4: Insuring Throughput

The three previous cases have emphasized the information collected about the facility the upgrade is taking place in. These cases showed the importance of having the right information from the sales phase up to the end of the implementation phase. Having the right information sets the foundation for the upgrade project to succeed by implementing it based on the information received. Having inadequate or wrong information is a recipe for failure, as shown in case 2. Cases 1 and 3 also demonstrate that the obtained information sets the progression speed of the project. It sets the drumbeat, which is also known as the throughput.

Throughput is known in industry as the rate of production, which means how fast raw material can be turned into a product ready for the market. In this case, a product is not produced, but a product is equipment installed. It means throughput is the rate of installation during a phase, or a portion of the production line is upgraded or replaced. Hence, throughput is the completion of the installation portion, also defined as tasks performed successfully during a defined time span. Each such time span is a phase within a project. Case 4 will show that up to this point, having all the information about the facility and how to integrate the project into it still is not enough to guaranty the desired daily throughput and ultimate success.

This case will draw the attention that concentrating on collecting only the information about the facility is not sufficient. It will not make it possible to have the desired throughput, even if the environment surrounding the project is constant. Constant in the fact that the team can start at the agreed times and no variation or disruption from the facility and also no surprises due to missing information. It will show that obtaining information about the team performing the upgrades is as important as collecting information about the facility. The capabilities of the team implementing a project influence the design of the upgrade. The skill and knowledge of the individuals performing the upgrade impact the progression of each phase in the project.

Like case 3, this case involves the replacement of a conveyor system. A previous similar project to case 3, where conveyors were replaced, experienced delays. The delays were due to performance issues with the installation team. The installation had conveyor motors with their field-installed VFD (Variable Frequency Drive) that is located not further than one to two meters from a motor. Each VFD communicates with the PLC (Programming Logical Controller) via ASi (Actuator Sensor Interface) communication. The installation of the new conveyors involves other similar projects, three types of skill sets. These skill sets are mechanical installers, industrial electricians, and a PLC programmer, and usually, the mechanical installers and industrial electricians are subcontractors, and the PLC programmer is not.

It was found that the major issue causing the delays in the above mentioned delayed project, was with the electric technicians, who were very good in their workmanship skills but lacked the understanding of the connections between the VFDs and the motors, even though the appropriate information was provided in a timely manner. These motors have a physical brake that is also controlled by the VFD, so there were nine connections, versus the traditional four-wire connections (L1, L2, L3 &Ground). The electric technicians had to be shown how to make the connections, and their work had to be audited to make sure there are no mistakes in the wiring. This situation caused delays, as the wiring of each motor took longer than expected. The throughput of the task sequence has suffered, and it took longer to finish the project.

Using a new subcontractor with the assumption that the technicians had the same knowledge base as the subcontractor the company usually used was an assumption taken with negative results. Documentations and circuit diagrams were provided to the new subcontractor, and since no questions were asked, it was assumed that all the information was clear.

On the other hand, the subcontractor made a similar assumption that the motors are traditional electric motors and did not bother to look at the information set received before the installation. The information was not passed to the electrical technicians, and they started the installation with a lack of information, which caused delays. In order to mitigate against a similar situation, a lesson was learned from the project that experienced the delays. The decision was made by engineering to simplify the installation methodology as much as possible. Such a simplification has a financial impact due to the following:

1. Negative financial impact.
    a. All motors and VFDs to be equipped with receptacles. This increases the cost per unit.
    b. Prefabricated cables with plugs to be used to interconnect the motors and the VFDs. This increases the cost per cable.

   c. A prefabricated cable with a plug on one end and flying leads (wires to be connected directly to the power connection) on the other, to be used for the power connection to the VFDs. This increases the cost per cable.
   d. There is an increase in engineering time to define the various length of cables and identifying all the needed hardware and accessories.
2. Positive financial impact.
   a. Reduction in the time used to connect each motor to a VFD.
   b. Reduction in the time used to connect each VFD to the incoming power.
   c. No auditing time needed, as the manufacturer tests all the connections of the cables.

The hardware cost increased by 12%, but the labor cost decreased by 15%. The physical labor in connecting the motors decreased substantially. However, the efficiency of the electric technicians dropped, since the installation of the conveyors mechanically still takes the same time and did not change. The savings are achieved by reducing the electric technician team by one member since there is more time for the rest of that team to do the necessary preparation work for the tasks downstream. What has been achieved is a greater chance of achieving the planned throughput. It is due to the reduction of risk in installation errors, as the connections have been checked prior to arriving in the field.

At first glance, the reduction in the electric installation per motor gives the urge to increase the number of equipment to be replaced per phase. Such a surge in throughput would be counterproductive, as the mechanical portion of the upgrade is dominant and would jeopardize finishing the installation of the equipment on time by the end of a phase and disrupt the facility's workflow. It is important to remember one of the important cardinal rules of DBR of not creating a constraint due to inertia (Goldratt & Cox, The Goal, 2014). It will just slow the throughput of the overall project. Further, the labor savings are only 15%, and the installation of one conveyor per task (phase of installation) takes between 25% to 30% of the allotted time span.

Case 4 points out a flaw in the previously defined methodology, which concentrated on only collecting information about the customer's facility and its workflow and how to integrate the upgrade activity within the facility's system. There is no mention of collecting information about the capabilities of the workforce that is assigned with the task of an upgrade. The emphasis of also collecting information on the skillset and knowledge of the workforce has been added to the third iteration of the methodology. Steps have not been added, but the steps concerning information and stakeholders have been expended to clarify the areas where information is of interest. The steps that have been expended to include the clarifications are:

Step 4

Define the Information needed

A-Internal

B-External

Step 5

Stakeholder Identification

A- Internal

1-Engineering

2-Programers

3-Field Service Technicians

B- External

1-Customer

2-Subcontractors

Step 6

Information collection and processing

A- Internal

1-Engineering

2-Programers

3-Field Service Technicians

B- External

1-Customer

2-Subcontractors

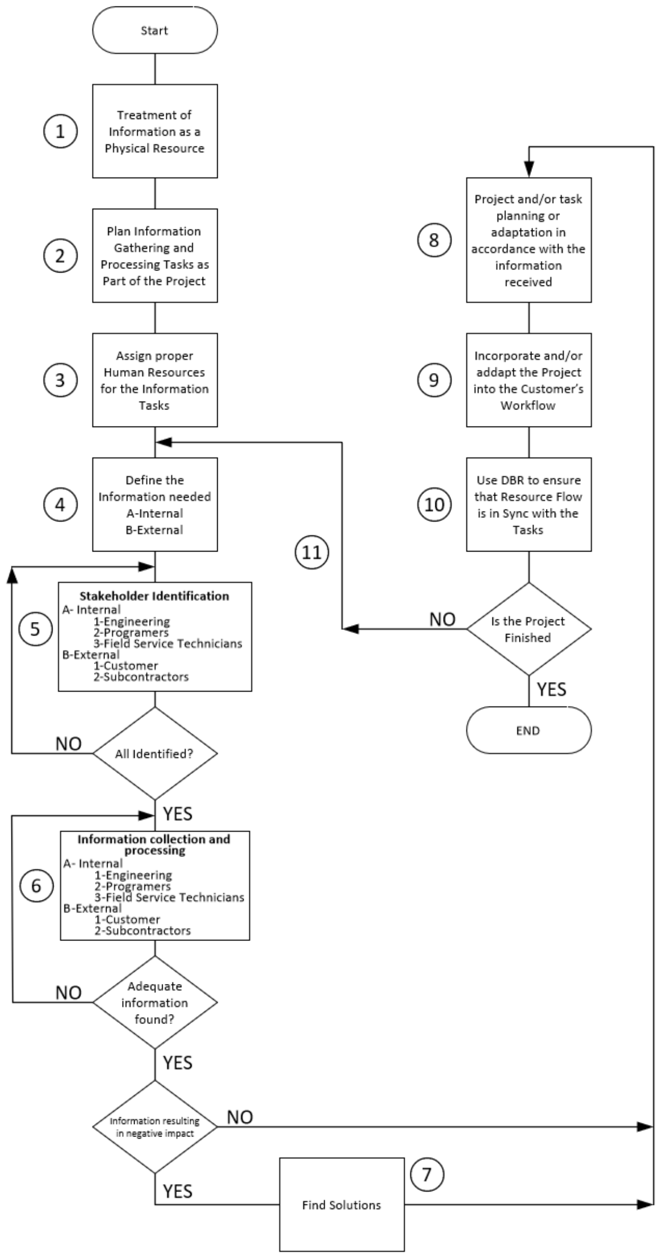

Exhibit 7 Revised Steps to Apply DBR to Phased Upgrade

The external information collected up to this point was concentrated on how to integrate the project into the facility's workflow in order not to disrupt it, but other external information has not been seriously considered. The realization that neglecting the information about the skill and knowledge level of the personnel implementing the upgrade can derail the best plans set and impact the facility's workflow negatively. The information collected is not limited to the external human resources, but also the internal ones. The capabilities of each member of the team internal or external have to be taken under consideration, and the upgrade activity planning fashioned accordingly.

CHAPTER 5

SUMMARY OF CASE ANALYSIS

5.1 Summary of Case Analysis

Four case studies have been analyzed based on the developed method of **Steps to Apply DBR to Phased Upgrade.** The initial application was applied to Case 1: Upgrading the Monorail System and to Case 2: Automated Tray Building System led to the revision of the method by adding an additional step. This step is to find information resulting in a negative impact on the upgrade operation and find an adequate solution. The succeeding applications of the method to Case 3: Induct Conveyor System showed a more comprehensive method to address the risk of disrupting the operation of automated distribution facilities undergoing phased upgrade. Case 4 showed that not considering the capabilities of the personnel implementing a project can derail the best-planned one. Insights from these four case studies can be summarized as follows:

Insight 1: The implementation of a phased upgrade project is a balancing act between resource flow and the customer's production environment. If either of them is not respected would result in failure with negative economic consequences. The key component is information, which is often overlooked as a resource. ToC gives the tools on how to ensure the harmonious progression of a project in accordance with the possible resource flow. No project can perform faster than the incoming resources. If these resources are bricks to build a wall and there is a shortage, then finishing it will be delayed. It is the same as the resource called information. If information is missing, one would not be able to make intelligent decisions. Any decision made in the absence of information is baseless and would lead a project in the wrong direction and cause delays, the same as the missing bricks.

Insight 2: ToC was effective in emphasizing when a phased upgrade project is progressing as planned with some time to spare, and the importance not to speed up the project without basing it on timely information. Speeding it up not based on information is a surge that will cause the balance between the resource flow and being a part of the customer's workflow to go out of balance. Such a situation will have negative impacts on both parties. This is the reason why it is important to follow the mitigation strategy shown in exhibit 6, with the DBR being the main part. It emphasizes the fact that a project will never progress faster than the capacity resulting from valid information collection and processing, the same as any physical resource.

Insight 3: Information must be treated as a resource in the daily decision making, so a phased upgrade project becomes a part of the functioning industrial environment the upgrade is taking place. It becomes a subsystem within the overall system. A subsystem can only function within the overall system adapting to the freshly received current information. The customer's operation varies according to the daily issues they face, as in any other business. The company performing the upgrade has to adapt and synchronize the daily activity with the customer in order to succeed in their mission. As they say: it takes two to tango.

Insight 4: ToC is a methodology of maximizing the throughput in production. Since our case is not producing a product to be packaged and sold, but a physical installation. The throughput is the speed of successful, timely installation. The success, as previously discussed, can only be achieved by treating information like a physical resource and making sure its flow is in sync with the field activity. This information flow helps in mitigating against wasting the second finite consumable resource, which is time. Inadequate, tardy, or wrong information will cause delays, which are usually difficult or impossible to recover. In order to prevent such a situation, the information collected should not be limited to the facility where the upgrade is being performed. It should also take into consideration information about the workforce implementing the upgrade. It is the reason why the design of the upgrade must also consider the ability of the implementation workforce as well as the state of the facility. They all will be temporarily a part of the same system and prevent any disruption during that time and ensure the maximum throughput of each phase.

Throughput and the efficiency of utilizing the workforce during the upgrade is a fine balance to be met. It is true that idle resources such as the electric technicians, in our case, waiting for the mechanical installers to finish their portion, could be looking at as a waste of resources. The difference is their inefficiency is by design. The priority is the throughput that must be maximized, and their efficiency is important at the time they perform their task. DBR sets throughput as the factor of most importance and not the overall efficiency, since throughput in any industry is the cash generator and not the overall efficiency of a workforce (Goldratt & Cox, The Goal, 2014). 99% efficiency of individual performing an installation can never be achieved and, at the same time achieving the maximum throughput possible (Goldratt & Cox, The Goal, 2014). Maximum throughput is only achievable through careful coordination of the activity of the personnel during the phases for the activities to work in harmony, even when it means that some resources will have to be periodically idle.

Insight 5: The actual state of the facility quite often lies in the tacit information that is only the knowledge of a few. A few that work daily in running and maintaining the equipment to make it perform to their desire to meet the targeted throughput. Quite often with the passage of time, some of the workforce with the tacit knowledge leave and do not transmit it to others, but this knowledge can be found within the equipment of the system. It is the changes found that is different from the explicit information. It takes time to find and analyze it in order to reconstruct what the tacit information is. It manifests itself in minor mechanical, electrical or program control changes done over time for one reason or the other.

CHAPTER 6

CONCLUSION

6.1 Conclusion

From the inception of this research, the concentration was in integrating the upgrade projects into the workflow of a facility without impacting the facility's workflow negatively. In doing so, there is a lot of information to be collected and processed. The information covers:

1. The various stakeholders throughout the structure and departments of the facility
2. The stakeholders within the company performing the upgrade
3. The status of the existing equipment and components
4. The status of the infrastructure (utilities, computer networks, etc.)
5. The existing workflow and its daily variations
6. The integration of the upgrade into the existing workflow

Case study 4 brought the realization that these 6 fields of information mentioned above are the essential ones. All the design and planning based on the information will achieve the goal if all the described 11 steps of the methodology up to case study 4 are followed. It becomes evident that it was only possible with a well-experienced workforce, but once a different workforce is utilized, success is not guaranteed. The information about their ability is missing. It becomes the same as acquiring material with the wrong specifications. Their information becomes as important as the facility's information to adapt a project accordingly.

Taking a holistic approach towards collecting information about all the resources and entities of the facility is essential to successfully perform an upgrade. Without this holistic approach, one will not develop an in-depth understanding of the system (Keating & Katina, 2011). Using the DBR method in this unconventional way is not unconventional. In a production environment, the resources are physical resources, such as material, subassemblies, equipment, workforce, etc. They are all a known entity, but there is an unknown in that environment, and it is defined as "statistical fluctuations" (Goldratt & Cox, The Goal, 2014). Statistical fluctuation is an unexpected event that one does not expect and does impact the throughput. The more information is gathered, the more one can hedge against the unexpected. The best way to absorb events causing delays by the statistical fluctuations is the creation of time buffers (Goldratt E. M., Critical Chain, 1997). Experience in the upgrade projects that a one to two-hour time buffer is planned in each of the daily phases. These time buffer sizes depend on many factors, but especially the skill and knowledge of the implementation workforce. They have the biggest impact, and the more is known about their capabilities, the better the planning of the individual phases, and the time buffer is possible. The time buffer is adapted daily according to the performance of the workforce and the better familiarity with the system the upgrade is taking place in. Basically, the time buffer is adjusted according to the situational information on hand. The less is known (lack of information), the larger the time buffer is, as the statistical fluctuation becomes dominant, decreasing the throughput.

DBR is an implementation methodology that helps in keeping the upgrade project in sync with the workflow of a facility. It acts the same as a PID (proportional–integral–derivative) controller in a system. It continually calculates the deviation (error) from the desired target and throttles or accelerates the system as needed. The accepted deviation from the setpoint is, in our case, the time buffer that is there to absorb the deviation, and the feedback loop is the rope, and the drum is the valve that controls the flow of information that drives all activities. If that medium going through the valve (i.e., drum) is in short supply, then the activity and the system will go out of control. The current methodology shown in exhibit 8 incorporates the effect of the internal information combined with the information on the status of the facility. All along step 10 "Use DBR to ensure that Resource Flow is in Sync with the Tasks" is a reminder to implement each phase following DBR's **P**rocess **O**f **O**n-**G**oing **I**mprovement (Watson, Blackstone, & Gardiner, 2007), (Goldratt & Cox, The Goal, 2014)., or better known as POOGI and making sure that all elements within a phase are moving in sync according to the weakest link. The weakest link is often caused by lack of information, and if it is ignored and the assumption is made that the necessary information has been acquired, but in fact, it is not, then the project will not be successful.

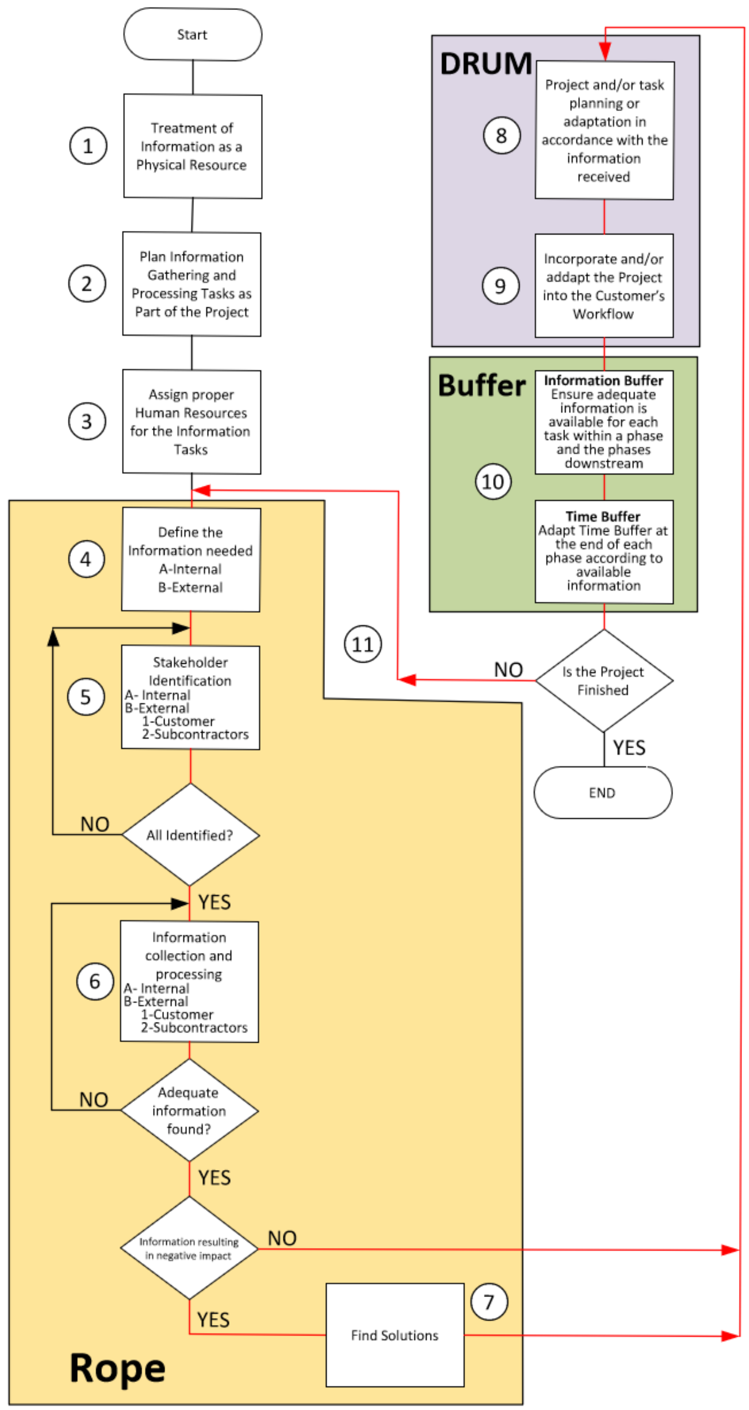

Exhibit 8 Current Steps to Apply DBR to Phased Upgrade

The current methodology shown in exhibit 8, shows that step 4 to 7 is the rope. The tasks downstream want to move faster and pull at the rope, but the rope will allow the forwards progression according to the information available. The drum is the planning and execution of the project in accordance with all the available resources, especially the available information and at last the buffer. The buffer is there to ensure that there is enough material in the form of information to fuel the project forwards.

On the other hand, the time buffer is more the shock absorber that dampens the fluctuations due to the statistical fluctuation. This fluctuation is due to influences from the facility, where for example, the equipment is not ready as promised in order to perform the upgrade and the influence of the human factor. One of the most influential factors mentioned in the paper is the knowledge base of the crew performing the upgrade. Having good information is the best resource that prevents surprises that potentially can derail such projects.

These surprises, known as statistical fluctuation or wandering constraints, is the biggest challenge as the work envelop changes constantly. It changes as these constraints pop up, and one deals with them, then the other manifests itself. The problem is they are not anticipated, and one is surprised by them. The surprise that the daily time span agreed upon to do the upgrades often changes, which makes the daily task planning challenging. The other unanticipated constraint is caused by the poor performance of the workforce in case 4. These statistical fluctuations also called “wandering constraints” that pop up in such projects when least expected.

The current methodology is applicable in industries where systems can suffer economic losses by the improper phased upgrade. These systems include a gamut from production lines producing commodities to facilities such as waste or water treatment plants. Such upgrade operations operate in a fluid environment with many unknowns.

What they all have in common is the question if all pertinent information has been found. Was something missed that could derail the upgrade project? Cases 3 and 4 showed that constraint arises unexpectedly due to sudden changes in the work envelope.

Hence, a potential area for future research is the exploration of wandering constraints such as changing start times that are constantly changing, or the unexpected discovery of the inability of some members of the upgrade team of performing as expected is a situation of not knowing what one does not know. The current methodology does provide the road map that guides phased upgrade projects based on the Drum-Buffer-Rope method developed in the Theory of Constraints. Even though DBR gives the foundation on which the current road map is, the more efficient identification of “wandering constraints” can further improve the current methodology.

BIBLIOGRAPHY

Cook, S. C., & Ferris, T. L. (2007). Re-evaluating Systems Engineering as a Framework for Tackling Systems Issues. *Systems Research and Behavioral Science*, 169-181.

Dekkers, R., Chang, C. M., & Kreutzfeldt, J. (2013). The interface between ‘‘product design and engineering’’ and manufacturing: A review of the literature and empirical evidence. *Int. J. Production Economics*, 316-333.

Deloitte. (2011, January 19). GLOBAL: More retailers record declining sales. *just - food global news*, p. http://proxy.lib.odu.edu/login?url=https://search.proquest.com/docview/854416448?accountid=12967.

E. Betterton, C., & CoxIII, J. F. (2009). Espoused drum-buffer-rope flow control in serial lines: A comparative study of simulation models. *Int. J. Production Economics 117*, 66-79.

Goldratt, E. M. (1990). *The Haystack Syndrom.* Great Barrington, MA 01230: The North River Press Publishing Corporation.

Goldratt, E. M. (1997). *Critical Chain.* Great Barington, MA: The North River Press Publishing Corporation.

Goldratt, E. M., & Cox, J. (2014). *The Goal.* Great Barrington: The North River Press Publishing Corporation.

Grimble, R., & Wellard, K. (1997). Stakeholder Methodologies in Natural Resource Management: a Review of Principles, Contexts, Experiences and Opportunities. *Agricultural Systems, Vol. 55, No. 2,*, 173-193.

Haltiwanger, G., Pinto, C. A., Landaeta, R. E., & Tolk, A. (2010). Understanding the relationship between Risk Management and Knowledge Management: a literature review and extension. *Int. J. Knowledge Management Studies*, 281-300.

Hansen, M. T. (1999). The Search-Transfer Problem: The Role of Weak Ties in Sharing Knowledge across OrganizationS ubunits. *Administrative Science Quarterly, 44*, 82-111.

Kacen, J. J., Hess, J. D., & Walker, D. (2012). Spontaneous selection:The influence of produc tand retailing factors on consumer impulse purchases. *Journal of Retailing and Consumer Services*, 578-588.

Katina, P. F., Keating, C. B., & Jaradat, R. M. (2014). System requirements engineering in complex situations. *Requirements Engineering*, 45-62.

Keating, C. B., & Katina, P. F. (2011). Systems of systems engineering: prospects and challenges for the emerging field . *Int. J. System of Systems Engineering*, Vol.2 Nos 2/3.

Kollat, D. T., & Willet, R. P. (1969). Is Impulse Purchasing is Realy a Useful Concept for Marketing Decisions? *Jurnal of Marketing*, Vol.33 / pages 79-83.

Liu, P.-L., Chen, W.-C., & Tsai, C.-H. (2005). An empirical study on the correlation between the knowledge management method and new product development strategy on product performance in Taiwan’s industries. *Technovation*, 637-644.

Nategh, M. (2009). Concurrent engineering planning on the basis of forward and backward effects of manufacturing processes. *International Journal of Production Research*, 5147–5161.

Prasad, B. (1996). *Concurrent Engineering Fundementals Vol. 1.* Upper Saddle Eiver, NJ: Prentice Hall PTR.

Sommer, A. F., Dukovska-Popovska, I., & Steger-Jensen, K. (2014). Barriers towards integrated product development — Challenges from a holistic project management perspective. *International Journal of Project Management*, 970-982.

Stern, H. (1962). The Significants of Impulse Buying Today. *Journal of Marketing*, Vol. 26, No.2, pages 59-62.

Tishby, N., Pereira, F. C., & Bialek, W. (2000). *The Information Bottleneck Method.* arXiv:physics/0004057v1[physics.data-an]24 Apr 2000.

Watson, K. J., Blackstone, J. H., & Gardiner, S. C. (2007). The evolution of a management philosophy: The theory of constraints. *Journal of Operations Management*, 387–402.

Zadnik, Z., Starbek, M., & Duhovnik, J. (2012). Enhancing preliminary design within concurrent engineering using the matrix of functions and functionalities. *Concurrent Engineering*, 275-285.

Zhang, J., Song, X., & Díaz, E. (2016). Project buffersizing of acritical chain based on comprehensive resource tightness. *European Journal of Operational Research*, 174-182.

Zins, C. (2007). Conceptual Approaches for Defining Data, Information, and Knowledge. *JOURNAL OF THE AMERICAN SOCIETY FOR INFORMATION SCIENCE AND TECHNOLOGY,*, 479–493.

VITA

Mr. Ferdinand Prantl is fulfilling the requirements for the Doctorate of Engineering from Old Dominion University in Norfolk, VA. Mr. Prantl currently works for Swisslog Logistics, Inc. in Newport News, VA as an Integration Manager, in the expansion of automated warehouses and distribution centers. He has over 35 years of international experience in industrial automation in the candy, pharmaceutical, water treatment, bookbinding, and logistics industries. Mr. Prantl graduated from the American University in Cairo, Egypt, in 1981 with a Bachelor of Science in Physics with a specialization in Solid States Electronics and a minor in Computer Science. He earned a Master of Engineering Management from Old Dominion University, Norfolk, VA in 2002.