Developing Key Performance Indicators (KPIs) for a Department Utilizing Environment Based Design (EBD) Methodology

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Abstract

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Maomao Pan

The research on KPIs has undergone substantial developments for the past few decades. Different users of KPIs often define the KPIs from different perspectives. Generally speaking, KPIs are quantifiable variables that indicate the efficiency and effectiveness of the performances of a product, a system, or personnel. Managers may use them to evaluate the performance of their team members in order to keep them on the right track; employees can use them to monitor his/her own performances and adjust accordingly; customers can use them to select their ideal products. This thesis focuses on developing KPIs for a department.

Currently, the methodologies of developing KPIs for a department are very limited. The dominate methodologies in both the research and practical world are Business Scorecards and Six Sigma. Both of them define the performance measurements from a high business level instead of providing much technical know-hows. Also, neither of them has addressed on how to prioritize the performance measurements. This thesis work proposes a new framework to systematically develop KPIs for a department utilizing Environment-Based-Design (EBD) methodology by treating “Designing KPIs for a department” as a design problem. A case study of applying the proposed framework

on an engineering department of an Engineering, Procurement and Construction (EPC) project in the oil and gas industry is also included in this thesis.

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Table of Contents

List of Figures

List of Tables

1. Introduction

1.1 Background and Motivation

Key Performance Indicators (KPIs) are quantifiable variables that can indicate the effectiveness and efficiency of performances(Camarinha-Matos & Afsarmanesh, 2008; A. Neely, Gregory, & Platts, 1995). KPIs have been one of the most critical business management tools and they can be tailored by each individual to fit for his/her own purposes. Managers may use them to evaluate the performance of team members and keep them on the right track. Employees can use it to monitor his/her own performances and adjust them accordingly (Eckerson, 2009b).

Driven by the growing global competition and in light of the Japanese Total Quality Management (TQM) theory popularized in the 90s, KPI has become a very popular research key word during the past few decades. The industrial practitioners and researchers have been exploring for the theoretical rationale behind the KPI and the framework of developing, implementing and maintaining the KPI systems. However, there are few methods focused on how to derive the KPIs. For the practitioners and researchers, the dominant frameworks are Six Sigma and Business Scorecards. Other than those, there does not appear to be any other frameworks with the same level of popularity (Katie Barry, 2006-20; Marr & Schiuma, 2003; A. Neely et al., 1995; Niedritis, Niedrite, & Kozmina, 2011; Parmenter, 2010). In September 2008, Eckerson (2009a) did a survey, it shows most of the companies don't adopt frameworks in developing KPIs. For those who do, the dominant methods are Business Scorecards and Six Sigma:

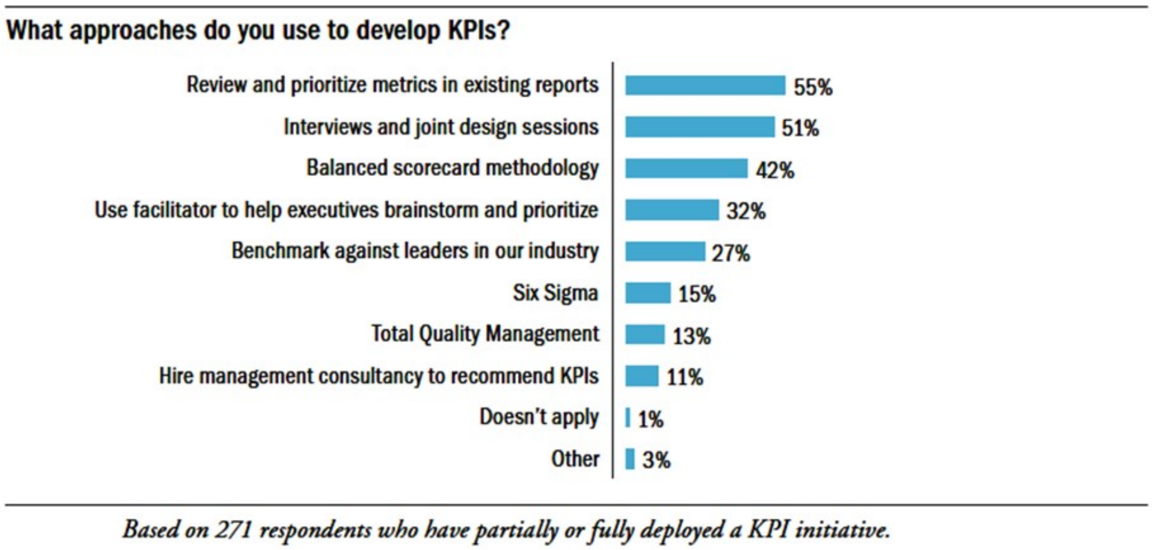


Figure 1. Methods Used to Develop KPIs

The original concept of Six Sigma is a statistical term meaning 3.4 defects per million units. Its core concept is to minimize the variability of the manufacturing (George, Rowlands, & Kastle, 2004; Pyzdek & Keller, 2003); However, the measurements that can be easily defined using Six Sigma in manufacturing processes can be hard to define in other types of processes; for example, the number of defects per million units may be meaningless to an engineering design process due to the fact that the engineering is highly creative and it is difficult to determine what are the defects and what are not. It is also commonly believed that the measurements defined in Six Sigma do not correlate with the business strategies. Measurements are recorded, but what these measurements mean to the success of the business as a whole is unknown (R. S. Kaplan & Norton, 2001).

The Business Scorecards is a top-down methodology to develop KPIs starting from analyzing business strategies from four perspectives: financial, customer, internal business, and innovation and learning perspectives. The measurements that reveal the effectiveness and efficiency of performances in terms of the above four perspectives are defined as KPIs. Business Scorecards can flow from high business levels down to lower business levels. By the time it reaches each department or team, the KPI system has grown over-complicated and is expensive to maintain (R. Kaplan, Kaplan, & Norton, 1996).

Both Six Sigma and Business Scorecards tend to develop the KPIs from a very high business level. They focus more on how the business implements the KPIs and provide general structures of developing, implementing and maintaining the KPI system, instead of much technical know-hows to derive the KPIs. Also, neither the Business Scorecards nor Six Sigma has addressed how to prioritize the performance measurements after they are identified. It calls for new KPI development frameworks to break the domination of Six Sigma and Business Scorecards, the frameworks that focus more on the technical know-hows instead of general guidance and also provide ways to prioritizing the performance measurements. This is one of the motivations of this thesis work.

Instead of using frameworks like Business Scorecards and Six Sigma, many researchers combine interviews, surveys, process modeling and decision making techniques together in order to develop process based or even activity based KPIs. The limit of the interviews and surveys is that they highly rely on expertise of the managers or other stakeholders. The assessment and answers are often subjective and non-precise. For the commonly used process modeling techniques such as Petri-nets, Workflow Nets, process algebra and etc. (van Hee, 2004). However none of these process modeling are particularly built for developing KPIs and the information included in each of them only reveals certain aspects of the process. One exception is the predicate Temporal Trace Language(TTL) proposed by Popova and Sharpanskykh (2008). It is an expressive process model that can include rich information such as the task description, task sequence, input and output resources, locations, the agents, goals, roles, constraints of each task and etc. However, its expressive nature decides it's a very tedious modeling methods and it is hard to explicit hidden information because not all the information is demonstrated graphically. This calls for new process models that are able to include all the information related to a business process and graphically demonstrate it in order to explicit the requirements or conflicts when extracting the KPIs. This is another motivation of this thesis work.

On the other hand, the Environment-Based Design has undergone over two decades of development. The main concept of the EBD is that: "*intuitively, design is an activity that aims to change an existing environment…design is driven by a need or an inspiration from the existing environment.* (Zeng, 2011a)". The EBD design theory contains a set of innovative concepts and tools to help the designer understand the nature of design, comprehend the design questions as well as to guide the designer conducting the design activities step by step. (Further details will be stressed in the theoretical foundation part of this thesis.) The theoretical and mathematical foundation of the EBD are built solid on the Axiomatic theory of design modeling (Zeng, 2002) and the recursive logic of deign (Zeng & Cheng, 1991).

The EBD theory contains a set of intuitive concepts and tools that can be used to resolve all kinds of design problems by providing a systematic framework to guide the design process. Meanwhile, it is also very flexible and can be tailored to solve problems of almost all kinds. One of the most critical tools in the EBD theory: Recursive Object Model (ROM) Diagram has a huge potential in process modeling. It was originally designed to model the natural language used in engineering design processes. Different types of boxes are used to represent the objects and different types of arrows are used to represent the relationships between the objects. It can almost represent all kinds of information graphically and completely. This is also one of the inspirations of this thesis research work.

In the path of becoming a mature design methodology, the EBD is currently at an era of seeking for real world applications and empirical studies. To date, the EBD theory has been applied on a variety of projects including quality management system development (Sun, Zeng, & Zhou, 2011), software design (Moroz, 2011), medical device design (Chen, Chen, Kong, & Zeng, 2005) and etc. However, the majority of the EBD case studies are the applications of EBD theory on product designs. There are few that focus on the business management. Therefore, it is needed to explore for new applications of the EBD theory on performance management--one of the most critical business management topics, and to testify its applicability. This forms another motivation for this thesis work.

To briefly summarize, this thesis work is motivated by the limitations of the current frameworks, to name a few:

- The most commonly used frameworks such as Business Scorecards and Six Sigma highly rely on the experience and expertise. The process of developing the KPIs are also highly manual and hard to realize computerization.

- Process-based methods of developing KPIs highly rely on process modeling techniques. However, the current process modeling techniques are not particularly designed for developing KPIs and are also lack the frangibility.

- The methods of prioritizing the KPIs, such as AHP and Fuzzy methods also highly rely on the experience and expertise. The results can be very subjective.

It is also inspired by the advantages of the EBD theory, also to name a few:

- It is a systematic analysis approach that can be used to solve all kinds of problems.
- It contains a set of tools such as ROM diagram and question asking procedures that can be used to model and analyses the business processes.

1.2 Objectives and Scope

This thesis has two objectives: one is to propose a new generic framework of developing KPIs for a department, utilizing the EBD methodology. The framework projected to be proposed is treated as a design problem.

The other objective is to conduct a case study to testify the applicability of the proposed framework on a real EPC project in the oil and gas industry.

The KPIs can be identified from three levels: strategic, tactical and operation level. This thesis focuses on the KPIs on tactical level, i.e. departmental KPIs.

1.3 Contributions

This thesis work has three main contributions.

(1) It is a contribution to the KPI research academia. A new framework of developing KPIs for a department is proposed in this thesis, seeking to break the domination of Six Sigma and Business Scorecards among the frameworks of developing KPIs. The framework proposed in this thesis emphasizes on technical know-hows to identify and prioritize the "performances" of a department instead of providing a general framework of developing, implementing and maintaining the KPI systems.

(2). It is a contribution to the development of the EBD theory.

Traditionally, EBD is used to develop products or services. This thesis work seeks for applying the EBD theory in the business management field and it is the first attempt to apply the EBD theory on developing KPIs, one of the most critical business management tools.

One of the most important tools of the EBD theory: Recursive-Object-Model (ROM) (Zeng, 2008) is innovatively used in this research work. The ROM is traditionally used in modeling textual information. In this research work, the core concepts of ROM are maintained, but it is adopted and tailored in order to model the business workflow. This demonstrates the flexibility of the ROM diagram and indicates its huge potential in the applications on many other subjects.

(3) It is a contribution to the engineering management.

Developing performance indicators in engineering management world is usually hard to achieve due to the fact that the engineering processes are highly interrelated and the design activities are naturally and highly creative. The case study conducted in this thesis work: developing KPIs for an engineering department from an EPC project, on one hand, testifies the applicability of the proposed framework; on the other hand, it is also an input to the engineering management world.

1.4 Research Methodology

This thesis research work will start from a comprehensive literature review on the definition of KPIs, the revolutions of the KPI development and the popular frameworks used for developing KPIs. A theoretical foundation of this research work will then be provided, where the core concepts of the EBD theory are reviewed.

"Developing KPIs for a department" will be treated as a design problem. The EBD theory will be applied on proposing the new framework of developing the KPIs. The traditional three major steps in the EBD theory: Environment Analysis, Conflict Identification and Solution Generation (Zeng, 2004) will be followed. The environment analysis will start from drawing a ROM diagram of the primary design question "Design KPIs for a department". The ROM diagram will be used as a guidance of the first round of environment analysis. Generic and domain questions will be asked in order to have a better understanding of the environment components and the product system, i.e. the KPIs. The ROM diagram will then be updated to include more detailed information generated during the question-asking section. The updated ROM diagram will guide the designer to having a better understanding of the design problem.

The business processes of a department will be modeled by ROM and the "actions" of a department will be identified according to the ROM diagram. The actions are the identified "performances" will then be prioritized based on two criteria: the cost of non-performance and the extent to which the performance is aligned with the mission/accountabilities/responsibilities of the department. The "performances" with the highest priorities will be considered as "key performances".

After the "key performances are identified", the next step will be developing the quantifiable variables to indicate the efficiency and effectiveness of the "key performances". The conflicts between the requirements of the indicators and the characteristics of the performances are identified and solutions to these conflicts will lead to the final design product: the KPIs for a department.

The framework of developing KPIs for a department, utilizing EBD theory will then be summarized into eight steps, followed by a case study of applying the proposed framework on an engineering department of an EPC project in the oil and gas industry.

1.5 Thesis Organization

The rest of this thesis is organized as follows:

Chapter 2 reviews the definition, dimensions, and revolutions of the KPIs, as well as the frameworks of developing KPIs; chapter 3 builds the theoretical foundation of this thesis. The EBD theory is introduced and its main concepts are addressed; chapter 4 demonstrates the processes of applying the EBD theory to create a framework of developing KPIs for a department. The proposed framework is summarized by eight main steps; chapter 5 applies the proposed framework in chapter 4 onto a real industrial project to develop KPIs for an engineering department of an EPC project; and chapter 6 concludes this thesis.

2. Literature Review

2.1 Definition of KPIs

Performance Measurement has long been recognized critical to the success of business management. A study conducted by Andy Neely (A. D. Neely, 2002) shows every five hours in every working day since 1994, one article or report is written on this topic. Simply type “Performance Measurement” in the Google Scholar search engine, over 3.2 million articles will pop out. Harvard Business Press and Cambridge University Press recently also published collections of articles on measuring corporate performances. Going hand-in-hand with the evolutions of the Intellectual Technology (IT), new software and tools have been constantly launched to this growing market as well (Marr & Schiuma, 2003).

KPI has been popularized among the companies in all kinds of industries. The KPIs developed can be tailored to each individual to fit for his/her own purposes. Managers may use them to evaluate the performance of team members and keep them on the right track. Employees can use it to monitor his/her own performances and adjust them accordingly (Eckerson, 2009b). Eckerson (2009a) did a survey and in-depth interviews with a dozen performance management practitioners and solution providers in 2008. 600 people participated in the survey and the majority of the survey respondents were corporate IT professionals or consultants working at large organizations across a broad range of industries in the United States. More than one third of them said they had either partially or fully deployed an initiative to KPIs, only 8 percent said they did not have KPI projects.

However, despite its popularity, it is anything but easy to develop the most suitable KPIs that have the focus, adaptability, innovation and profitability that the senior leadership has been looking for. For the past decades, the existing KPIs adopted by companies are too often found lack of focus, lack of linkage to the critical success factors, or miss-used. Managers constantly find that much energy and resources were spent on developing and collecting the KPIs but no profound differences were made to the business success.

Perhaps this is due to the huge diversity of the definition of KPIs (Parmenter, 2010). The Performance Measurement is a concept that has constantly been talked, developed and even applied, but rarely defined. Take a look at each word, Performance, for example, as Altshuller (1984) defined: "*According to the marketing perspective, organizations achieve their goals, that is they perform, by satisfying their customers with greater efficiency and effectiveness than their competitors*." This does not give a direct definition on what a performance is. Moreover, as it is only from a marketing perspective, it does not seem proper to generalize and extend it to other perspectives. Many scholars identified various dimensions of performances. For example Sink (1985) did mention that Performance consists of seven dimensions, i.e. Effectiveness, efficiency, quality, productivity, quality of work life, innovation and profitability. Maloney (1990) also gave a comprehensive review on performance. But none of them directly addressed the definition of the performance. In this thesis work, the performance can be defined as the effectiveness and efficiency of a department, a process, a product or personnel. The performance measurement, therefore can be defined as quantifiable variables that indicate the performance level (A. Neely et al., 1995).

If Performance Measurement is defined, then what is KPI? The modern definition of KPI derives from Performance Measurement. Most scholars believe that among the matrix of all the Performance Measurements, which are defined as quantifiable metrics used to quantify the efficiency and/or effectiveness of an action, only those and a few in align with the strategic objectives of an organization and reflect the strategic value drivers rather than measuring non-critical activities and processes are defined as KPIs. (Bauer, 2004a, 2004b; Eckerson, 2009a).

Albert Einstein once said: "*Not everything that counts can be counted, and not everything that can be counted counts.*" After all, Performance Measurement does not come cheap. Measuring every possible measurement is luxurious and wasteful. The cost of measurement is an issue of great concern to managers (A. Neely, Mills, Platts, Gregory, & Richards, 1996). R. S. Kaplan and Norton (1996) suggested that no more than 20 among the Performance Indicators can be Key Performance Indicators while Hope and Fraser (2003) suggested fewer than 10 Key Performance Indicators should be developed.

2.2 Key Performance Measurement Categorization

Performance measurements have huge diversities in terms of its definition and dimensions. By scientifically categorizing the performance measurement, both researchers and practitioners can understand and apply them better.

Performance measurements are often categorized as “lagging” indicators and “leading” indicators (Ghalayini & Noble, 1996). Lagging indicators provide the historical information that measures past performance. Lagging indicators typically focus on the “output”. They are often called “outcome measures” or “performance results”. They are easy to measure but hard to improve. Examples can be: sales/shipments, financial statements, loans, scour/record.

Leading indicators provide the information that drives or can be correlated with future performances. Leading indicators are often “input oriented” and are also often called “performance drivers”. Leading indicators enable the practitioners to take pre-emptive actions to improve the chances of achieving strategic goals. Leading indicators are often captured at the level of each individual process and are usually hard to measure and easy to influence. Examples can be: leads/orders, new products, interest rates, and resources.

However, the idea of categorizing the KPIs into leading and lagging indicators is not always favored. R. Kaplan et al. (1996), for example, believe the fact that defining leading indicators as those measurements that can provide predictive information contradicts to the reality that some driving relationships may come from external factors that are almost impossible to measure, such as the market, the competitors and etc. Parmenter (2010) also believes categorizing the KPIs into leading and lagging indicators is confusing and ad-hoc because a leading indicator for one action can often also be a lagging indicator for another action and vice versa. For example, the late-planes-in-the-air can be a leading indicator in terms of taking actions to catch up with the time to ensure the plane eventually land on time. On the other hand, it can also be a lagging indicator because it is already happened and there are certain unavoidable consequences to bear, such as the extra fuel consumed to speed up the airplane, the extra duty created to the environment and the customers' dissatisfaction to the service.

Instead, David Parmenter *et al* (Niedritis et al., 2011; Parmenter, 2010) classified the Performance Measurements into four types: Result Indicators (RIs), Key Result Indicators (KRIs), Performance Indicators (PIs), and KPIs. RIs represent the activities within the business success factors and usually are the results of more than one activity. All the financial measures are RIs because they only provide the information of the outcomes of multiple activities but do not indicate how each specific activity affects the results. KRIs represent the few RIs that are in align with the critical business success factors. They are able to provide ideal consulting information to people that are interested in the organizational performances but do not involve in the day-to-day management, namely the board or customers. The monitoring cycle is typically long. It can be monthly, quarterly, even annually. KRIs can be either financial or non-financial. KPIs, on the contrary, are often measured much more frequently than the KRIs. It can be hourly, daily or weekly. A KPI measures a specific activity thus they are able to provide information on what to do in order to improve the final outcome. Finally, KPIs are able to indicate what needs to be done in order to dramatically increase the performance level. They:

"*represent a set of measures focusing on those aspects of organizational performance that are the most critical for the current and future success of the organization.*" (Parmenter, 2010)

2.3 Dimensions of Performance

What are the dimensions of performance? What kind of information should the performance measurements imply? It is also a debatable question that different researchers cannot share the same stance. It may be because of the diversity of the nature of performance measurement. For researchers from different background or different disciplines and managers from different fields, performance can have significantly different meanings, thus the performance measurements need to imply the corresponding information of different dimensions. SinkSink (1985) proposed that the performance should consist seven dimensions: effectiveness, efficiency, quality, productivity, quality of work life, innovation and profitability. These seven dimensions have been agreed, confirmed and applied by many researchers from different fields including construction management, operational management, and etc. (Maloney, 1990). Leong, Snyder, and Ward (1990) summarized that the key dimensions of performances in manufacturing can be defined in terms of quality, delivery speed, delivery reliability, cost and flexibility. Fujimoto (1989) pointed out that the quality of a performance is an output of quality management practices and based on their work, the quality performance can be categorized into internal quality performance, i.e. conformance to specification, and external quality performance in the market place, i.e. quality-in-use and customer satisfaction.

From different perspectives, performance has different meanings. Nevertheless, A. Neely et al. (1995) believe that fundamentally, different dimensions of a performance can be summarized into effectiveness and efficiency. Effectiveness means to which extend the purposes of an action are reached, while efficiency means how economically the resources are utilized along the way to reaching the goals of an action or actions. For example, product reliability, as the quality-related dimension of the performance, can also be understood in terms of effectiveness and efficiency, i.e. a higher level of product reliability may lead to higher customer satisfaction and reduce the cost by decreasing field failure and warranty claims. Neely *et al* also further addressed that how the efficiency and effective dimensions relate to quality, time, cost, and flexibility.

Aside from the huge diversity in defining performance dimensions, another challenge is the difficulty to quantify them. For example, effectiveness is often defined as the attainment of the organization's objectives. But how to justify to what extent have the objectives been met? Take another example, flexibility, the definition itself is debatable, let alone its measurements (A. Neely & Wilson, 1992). Gerwin (1987) pointed out the lack of operational measures of flexibility. Even for productivity, one of the most commonly agreed performance dimensions, its measurements in manufacturing industry is not hard to define, but many literatures indicate its insufficiency in complex and innovative systems such as the engineering design system (Georgy, Chang, & Zhang, 2005a; Thomas, Korte, Sanvido, & Parfitt, 1999).

As a matter of fact, each aforementioned performance dimensions itself has debatable meanings and their quantifications heavily rely on the understanding of the nature of its applications, empirical studies and the suitable mathematical tool sets. Because of this, the quantification of the performance dimensions forms an independent research field of its own right.

2.4 The Evolution of Performance Measurement

The ultimate goal of Performance Measurement is to make the profit companies more profitable and the non-profit companies better satisfy their customers (R. Kaplan et al., 1996). Thus it is not hard to imagine that the evolution of the Performance Measurement goes hand-in-hand with the economic development and is grounded on the industrialization history for the past decades. It is of the author's interest to give a brief review on the evolutional path of the Performance Measurement so that the readers can have a better understanding of this research topic.

As a matter of fact, people's desire to quantify and measure dates back to centuries ago. Lord Kelvin (1824-1907) once said, "*When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it and express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of science, whatever the matter may be*." (1883)

This desire to measure probably had not been extended to the management world until Peter Drucker published the book named *The Practice of Management* in 1954, in which he argued that the desire to quantify could potentially be satisfied by introducing balanced sets of measuring including market standing, innovation, productivity, physical and financial resources, profitability, manager performance and public responsibility. (Drucker Peter, 1954; Drucker, 1995; A. Neely et al., 1995). Interestingly, for the GM, this book was unjustified, disappointing and offensive because instead of advocating the glowing success of General Motor's success, Drucker suggested GM to re-examine its long-standing policies on customer relations, dealer relations, employee relations and more. This is a reflection of the historical background: during the 1950s, the United States, with the World's biggest economy, had dominated many advanced industries while the other countries were too busy recovering from the wars. The managers felt so secured that seeking for improvement by using tools, such as performance measurement, can hardly be the first thing on the agenda. On another note, the grounding theory of the performance measurement, the business management, is a new concept at the time.

In the 1970's manufacturing world, the Big Three: Ford, General Motors and Chrysler (Vlasic, 2011) continued to dominate the American Market with a share of over 90%. AT&T monopolized the telephone industries. Intel took the place to be the computer chips leader by introducing a new generation of computer chips. Most of the industry tycoons held such a huge share of the market that they simply did not have much motivation or initiative to seek for better relationships with customers. Employees weren't mobile. Most of them spent their entire careers in the same company. The organizational structures of the companies were mostly the vertical structure type, which is so dull that it prohibited the cross-functional cooperation. Launching a new product or making a change often took too much time. Especially due to the energy crisis in the 70s, the market demanded highly fuel efficient automobiles but the prolonged processes resulted in a long time for designing and launching new models. The inflexibility made the American automobile tycoons uncompetitive against the rising Japanese automobile manufactures and quickly they almost lost 30 per-cent of the American market. On the other hand, the Japanese manufacturing started to flourish by adopting America's management theories, including Peter Drucker's theory. The quality was solely defined in terms of the conformance to specification and the final financial benefits. Performance Measurement were often focused on the product defects and the Return on Investment (ROI) that was originally developed by the three DuPont cousins for their diverse business interests in the 1900s (Davis, 1999; Frum, 2008; A. Neely et al., 1995; R. F. Smith, 2007; Vlasic, 2011).

In the early 1980s, the intensive international competition forced the big companies that dominated the market for decades to seek for changes. However, most of the American auto tycoons were faced with severe downturn. Chrysler was near bankruptcy Ford was nowhere better. General motor survived but still lost over 30 per-cent of its market share. The performance measurement research world was concerned about the data envelopment methodology and later in the 1980s, with the popularization of the concept of TQM, scholars started to seek for the linkage between the performance measurement and the business strategies. The quality emphasis was shifted from the conformance to specification to customer satisfaction. The workforce was becoming more mobile and more and more companies had built cross functional teams. With the increasing utilizations of the process analysis tools such as Flowcharts and process mapping techniques, the business processes were able to understand them from a more micro level (R. F. Smith, 2007).

The 2000s marked the new era of performance measurement. Due to the growing globalization, the processes were further complicated. A typical organization has thousands upon thousands of processes that are inter-dependent on each other and conducted by multiple partners or contractors, as well as their sub-contractors. This drove the business management to become much more process-oriented and dependent on human relationships, system capacity and networks. On the other hand, the management software are springing up, paving the way to more efficient process management.

The Business Scorecards has dominated the performance measurement framework for more than a decade. However, the scholars have also been seeking for other methodologies that can be utilized to develop performance measurement. As the Business Scorecards has already been adopted by many companies and have been in use for many years, much data are in place for empirical studies on comparing and verifying other methodologies that can be utilized to develop performance measurement. The Performance Measurement researches started to call upon more robust theoretical and empirical studies on performance measurement frameworks. (Banker, Potter, & Srinivasan, 2000; Ittner & Larcker, 2003; A. Neely, 2005)

2.5 Frameworks of Developing Key Performance Measurement

After World War II, several national economies rose and it led to a global competitive environment, thriving for better performance management. Following the popularization of the Japanese TQM, a set of frameworks to develop the performance measurements were proposed and developed to control and improve the performance of business processes, such as the Balance Scorecard, performance prism, performance measurement matrix (Keegan, Eiler, & Jones, 1989), the results and determinants framework, SMART pyramid, and etc. (Kennerley & Neely, 2002).

Perhaps the most popular framework of developing the performance measurement is Balanced Scorecard proposed by Kaplan and Norton (R. Kaplan et al., 1996). A research shows over 60 percent of firms have adopted the balanced scorecard (Rigby & Bilodeau, 2007). The underlying concept is that in contrast to the traditional short termism financial measurements, performance needs to be measured in a more holistic way. Kaplan and Norton proposed that the business performance need to be measured from four perspectives, i.e. financial, customer satisfaction, internal process and learning and growth. Parmenter (2010) believes that two other perspectives: environment/ community and employee satisfaction also need to be included. The Balanced Scorecard approach is rather a general guidance than stone casted. It can be tailored and adapted to fit for the specific purposes of an organization or industry.

The typical procedures of utilizing Balanced Scorecard to develop KPIs can be:

1. Firstly, the mission, values and vision of an organization need to be understood. 2. Strategy Maps can be formed. 3. The performance measures, targets and initiatives can be developed from the aforementioned four perspectives of the business performance, referring to the strategy maps. The way to coming up with the performance measures is normally brainstorming and consensus, i.e. bringing in experienced people that understand the business processes to go through each perspective and come up with the measurements based on their own experience and judgment. 4. Filter the candidate performance measurements by analyzing the alignment with the strategy, the feasibility, and etc. 5. Form the scorecards and implement it.

Parmenter (2010) proposed a 12-step model to developing KPI based on the Scorecard Concept: Step 1: senior management team commitment; Step 2: establishing a wining KPI Project Team; Step 3: establishing a "just do it" culture and process; Step 4: setting up a holistic KPI development strategy. Step 5: marketing the KPI systems to all employees. Step 6: identifying organization-wide critical success factor. Step 7: recording performance measurement in database. Step 8: selecting team-level performance measures. Step 9: selecting organizational winning KPIs. Step 10: developing the reporting framework at all levels. Step 11: facilitating the use of winning KPIs. Step 12: refining the KPIs to maintain their relevance.

The advantages of the Business Scorecard framework are that it emphasizes on integrating different dimensions of performance and it implicates a lot of flexibility. But the Balanced Scorecard is more of developing the KPIs from a strategic level. Although work groups or departments are suggested to use Balanced Scorecards to develop KPIs, integrating performance management from a more detailed level, it often over-complicate the performance management system. On the other side, as the Business Scorecards flow down along the business organization hierarchy, the mission and vision become more and more functional, revealing less and less strategic business visions. The performance measurements developed, thus become distant even irrelevant to the business strategies. This beats the whole purpose of adopting Business Scorecards.

Before the Business Scorecards, Six Sigma was a popular framework of developing KPIs. It was believed to be a concept that was first embarked by Motorola in 1960s (G. Smith, 1993), and it was popularized in the 1990s. Six Sigma was originally a statistical term that refers to 3.4 defects per million opportunities and it has already been developed in a whole business management and process quality management tenets, equipped with a variety of tool sets. Although the original purpose of Six Sigma was to control and improve the manufacturing processes where quantifiable information is easy to obtain, its application has been extended into many other areas including marketing, customer order processing, and etc. In the application of developing the KPIs, Six Sigma has also been used as a framework to guide developing, implementing and maintaining the KPIs of the business processes.

A typical procedure of utilizing Six Sigma is: Define, Measure, Analyze, Improve and Control. Define is to identify the problem or areas of improvement. The critical business success factors were defined during this step. Measure is to identify what parameters to measure. Various statistical techniques including scatter plots, ANOVA (Analysis of Variance) were applied during this step. Common measurements are the averages and variations of the measured parameters. Based on the data collected, an analysis can be conducted. Root causes of the abnormal measurements are expected to be found. Tools like Pareto Charts, Cause-and-Effect Diagram, Fish Bones, and etc. can be used. After the root causes are found, actions are expected to take place in order to make the process improvements. The final step, Control, is to control the improved processes and sustain the Six Sigma initiative by leveraging statistical methods such as Control Charts.

The advantage of Six Sigma is that it introduces a set of statistical tools to monitor the process performance. The limitations of Six Sigma are that it focuses on performance at the process level but there's no guarantee that the performance measured are aggregated to the corporate wellness and are able to reflect the business's strategic visions. These limitations motivated Kaplan and Norton to propose the very popular Star in the KPI development academia: Business Scorecard.

Although the Six Sigma and Business Scorecard have been recognized as frameworks of developing KPIs, the techniques used in these two frameworks are rather superficial and empirical that barely touch the technical know-how of how to set up the scientific performance measurements.

Since the 2000s, the process performance has been recognized as the most critical driver of organizational success (Alonso, Dadam, & Rosemann, 2007; R. F. Smith, 2007). More and more researchers derive the process-oriented even activity-based KPIs by leveraging the process modeling tools and decision making techniques. For example, the Workflow Management Systems (WfMS), the Petri-Nets, Workflow Nets, process algebra and etc. are often utilized in process analysis. Each of them has its own advantages and disadvantages (van Hee, 2004). And the most commonly used decision making techniques probably are the Analytical Hierarchical Process (AHP) and multi-criteria decision making methods such as fuzzy sets formalization. For example, Shahin and Mahbod (2007) used AHP to prioritize the SMART KPIs; Masood, Jahanzaib, and Akhtar (2013) used AHP to prioritize the importance of departments in automobile parts producing sectors. Kachitvichyanukul, Luong, and Pitakaso (2012) proposed a hybrid Multi-Criteria Decision Making (MCDM) approach, which include fuzzy, Delphi method and AHP in order to select KPIs for solving coordination problems of multinational firms. For the fuzzy sets method, examples can be found in Parreiras and Ekel (2011), Berrah, Mauris, Haurat, and Foulloy (2000)'s and Yu and Hu (2010) work. Other examples of multi-criteria decision making can be found in Bititci, Suwignjo, and Carrie (2001), and Clivillé, Berrah, and Mauris (2007)'s work.

Interestingly, Popova and Sharpanskykh (2011) developed an order-sorted predicate Temporal Trace Language (TTL) based on an expressive language (Popova & Sharpanskykh, 2008) and derive the KPIs by analyzing the internal and external for the organization, such as company policies, mission statements, business plan, job descriptions, laws, domain knowledge, etc. The expertise of domain experts, managers and other involved parties are often used considering the input information for extracting the KPIs are often incomplete and imprecise. The performance indicators and relationships between them are modeled and analyzed.

Another question is, while all these frameworks proposed are busy developing performance measurements, how can we validate them? Up to date, a few methods have been proposed. Georgy et al. (2005a) applied the Neurofuzzy approach, which is known for its robustness in solving problems involving complex relationships in estimating the engineering performance. And the case study they conducted showed promising results. Sandhu and Gunasekaran (2004) applied the Comprehensive Quality Functional Deployment (QFD) Matrix approach to develop the KPIs for the Education Ministry of the State Government of Guanajuato in Mexico, seeking for the interrelations between the indicators and the internal processes. Georgy, Chang, and Zhang (2005b) employed multiple attribute utility functions approach in assessing engineering performance in a construction project. An assessment of the total project engineering performance was provided by integrating together the individual performance measurements, taking into consideration of their relative importance.

3. Theoretical Foundation

3.1 Introduction

In this thesis work, the EBD theory, which was introduced by Dr. Yong Zeng in 2004 is the main technique utilized. The EBD stems from the observation that a design aims to change an existing environment to a desired one by generating a new artifact. In EBD theory, it is believed that the whole universe contains two parts: the product that is to be designed and its environment and a design "*starts from the environment, functions for the environment and brings changes to the environment*" (Zeng, 2011a).

The EBD theory is not only literally descriptive. It is also developed based on profound mathematical foundations and is originated based on the Axiomatic Theory of Design Modeling (Zeng, 2002, 2011a). The following mathematical symbols are used in EBD (Zeng, 2002):

1. Predicate symbols: $\supseteq$ (inclusion), $=$ (identity), $\neq$ (inequality)

2. Operation symbols: $\cup$ (union), $\cap$ (intersection), $\otimes$ (relation), $\oplus$ (structure), Θ (range)

3. Logical symbols: $\neg$ (negation), $\wedge$ (conjunction), $\vee$ (disjunction), $\forall$ (universal quantification: read as "for every"), $\exists$ (existential quantification: read as "there exists one"), $\exists!$ (existential quantification: read as "there exists exactly one"), $\rightarrow$ (logical implication), $\leftrightarrow$ (if and only if), $\overset{\Delta}{\leftrightarrow}$ (defined by) (Zeng, 2002)

As a comprehensive design methodology, The EBD theory can be seen as a system of procedures to support designers in design activities that involve three main objects: the designer, the environment in which the product is expected to work and the product and a product, i.e. any artifact to be designed and added to the environment. (Zeng, 2004). Theoretically, anything except the product can be seen the environment. Practically, however, only the environment components having direct impact on the product need to be considered.

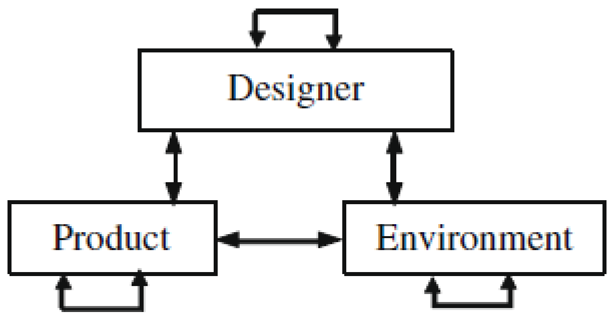


Figure 2. Design Activities (Zeng, 2011b)

The EBD Methodology contains a whole set of core concepts to help the designers understand the nature of design, as well as tool kits to provide step-by-step guidance through the design activities, leading to a successful design. Generally, the EBD includes three main steps: environment analysis, conflict identification, and concept generation (Zeng, 2004). These three steps work together progressively and simultaneously to generate and refine the design specifications and design solutions as shown in Figure 3:

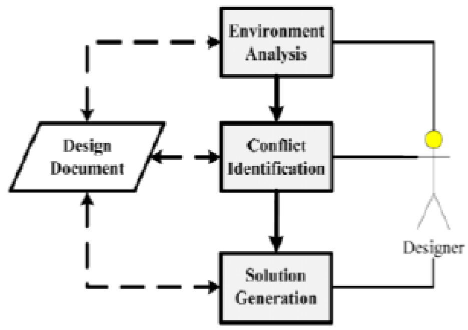


Figure 3. Design Process Model (Zeng, 2002)

In this chapter, the core concepts underlying the EBD theory will be addressed.

3.2 Core Concepts in the EBD Theory

1) The environment can be infinitely decomposed

One of the core concepts in the EBD theory is that everything in the universe can be seen as an object, including the interactions between objects are also objects; and every object in the universe contains other objects. Symbolically it can be expressed as:

$$A \supseteq B, \forall A \; \exists B \tag{1}$$

Where B is one sub-object of A. $A \supseteq B$ is read as "A includes B", $\forall A$ is read as "for every A" and $\exists B$ "there exists one B".

Logically, an object can be infinitely decomposed. But realistically, due to the limit of the capacity of human cognition and the scope of the design, an object can be broken into a limited number of sub-objects, which cannot or need not be further decomposed. These sub-objects are defined as "primitive objects".

If an object O can be broken into m sub-objects:

$$O = \bigcup_{i=1}^{m} \quad 1, 2, \ldots, m) \qquad (2)$$

In a design problem, the object is often the “product” and sub-objects are referred as “components”.

For one design question, different designers may decompose it in different ways. As the knowledge, thinking pattern and background of the designer vary. Different designers probably will decompose the environment in different fashions, which may eventually lead to different solutions, i.e. different product designs.

2) Objects do not stand alone; they are related to each other.

The EBD theory believes that there are relations between objects in the universe. If we denote two objects by A and B, symbolically it can be expressed as:

$$A \otimes B, \forall A, B \qquad (3)$$

Where $A \otimes B$ is read as “A related to B”, $\forall$ is read as “for every”.

The relationships between two objects are also objects. Thus when decomposing an object, the relationships among its sub objects should always be attached, implying that “*the whole is greater than the sum of the parts* (Zeng, 2002)*”*.

If denote the structure of an object O by $\oplus O$, it can be expanded into:

$$\oplus O = O \cup (O \otimes O) = (\bigcup_{i=1}^{m} \quad \cup \bigcup_{i=1}^{m} \bigcup_{\substack{j=1 \\ j \neq i}}^{m} \quad {}_{j})) \tag{4}$$

3) Conflicts are the driving force of the design; resolving the conflicts is the ultimate goal of a design.

Before a design, the environment, i.e., the universe as a whole is static. Each of its components stays in harmony with each other. Until one day, for whatever reason, a conflict appears within this environment, the harmony is broken and it calls for a design to resolve this conflict (Zeng, 2004).

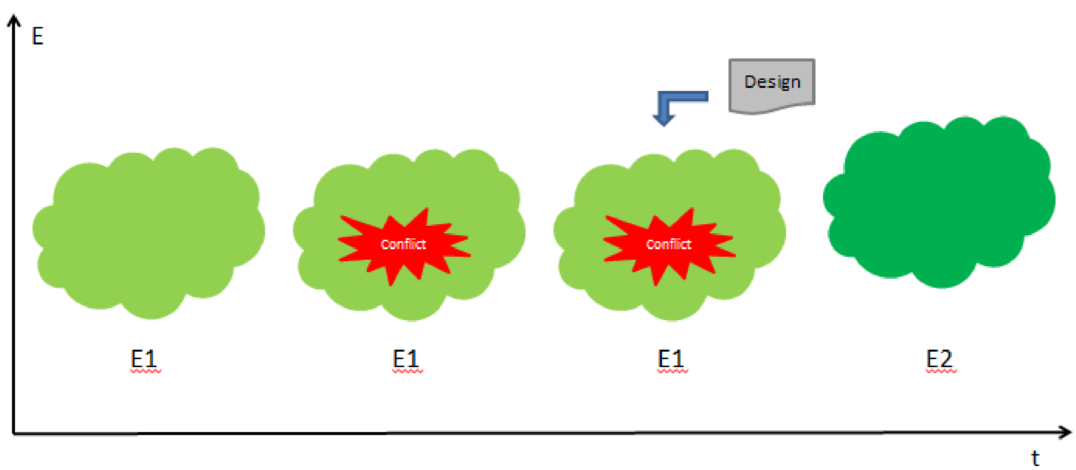


Figure 4. Conflict Being the Design Driving Force

But what is a conflict? The definition of a conflict varies as the research focuses vary. Harrington, Soltan, and Forskitt (1995) defined that a conflict is disagreement between two or more viewpoints on some decision or values proposed in design. Some scholars classify the conflicts first then define each of them. For example, Altshuller (1984) categorized the conflicts into three groups: administrative conflicts, technical conflicts, and physical conflicts. Barber et al Hanna and Barber (2001) defined goal conflicts, plan conflicts, and belief conflicts. In EBD design theory, "*a conflict happens when there are competing relationships between two things over another (third) issue or object*" (Yan & Zeng, 2011).

4) A conflict resolution can be found if the conflict is fully understood.

As explained in the previous paragraph, a conflict is the driving force and the motivation of a design, thus it can be understood as design requirements. Design is an intelligent activity that begins with design requirements and ends with a product description (Zeng & Gu, 1999a), i.e. in the EBD theory, the design can also be defined as an intelligent activity that begins with a conflict raised from the environment and ends with a solution description, as is shown in Figure 4.

The first step in product design is to translate design requirements, i.e. the conflicts into design specification and eventually map the design specifications into product descriptions (Figure 5) (Zeng & Gu, 1999a).

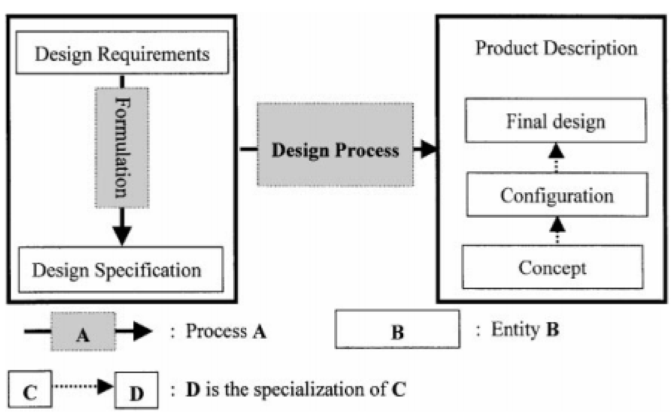


Figure 5. Design Activity (Zeng & Gu, 1999b)

At the beginning of a design, the designer's understanding of the conflict can be very limited. The designer only knows that the product he/she is going to design falls within an environment. But the boundary of the product environment cannot be clearly defined because the product is yet unknown. The product boundary should be very broad at the beginning stage of a design. As the design develops, the designer gains a deeper and more comprehensive understanding of the design problem thus the design space is narrowed down because there are less unknown (Shown in Figure 6). After rounds and rounds of analysis, the design problem is eventually fully understood. All the unknown parts disappear and the design boundary is fixed. The final design product becomes obvious. The product descriptions thus can be easily achieved and the design goal is eventually reached.

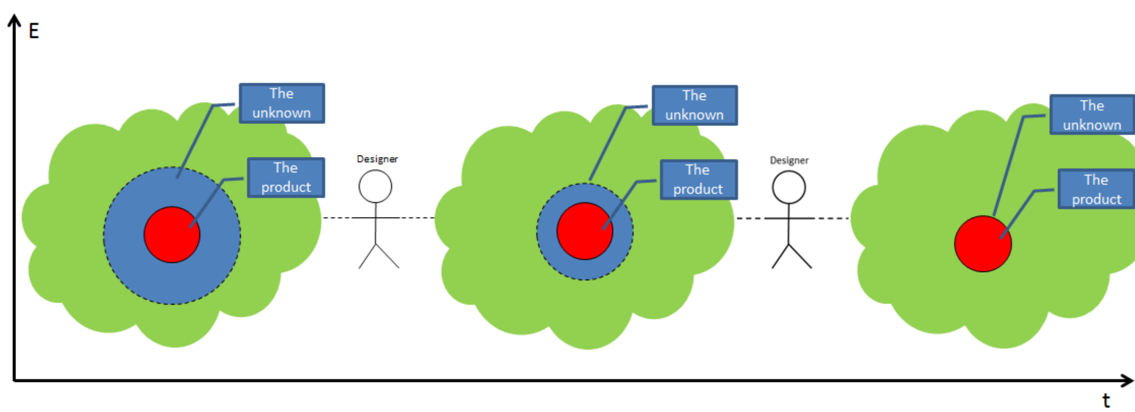


Figure 6. Recursive Design

5) Use the known to solve the unknown-the recursive nature of design

In the EBD theory, the logic of design is recognized as recursive, i.e. during the design process, the generation and evaluation of design solutions depend on design knowledge while the kind of design knowledge that can be used for the current design is determined by the design solutions. This recursive concept has been recognized as the "co-evolutionary" nature of the design process in which design problems, design solutions, and design knowledge are updated simultaneously (Dorst & Cross, 2001; Maher & Tang, 2003). As the design process is moving forward, the design requirements (i.e. the understanding of the design problem), the design solutions as well as the design knowledge change simultaneously and interdependently.

Typically, a design process is divided into three stages: conceptual, configuration and detailed design stages (Gu, 1998). However, in EBD theory, a design does not have explicit boundaries between design stages. The design process is a recursive process, i.e. every earlier design stage will generate new design requirements or refine the original design problem. If the design solution is denoted by S ; the design requirement is denoted by R_d and the design knowledge by K_e , at different time (t_i), S , R_d and K_e have different values. The co-evolution of the design solution, design requirement and design knowledge can be shown in Figure 7.

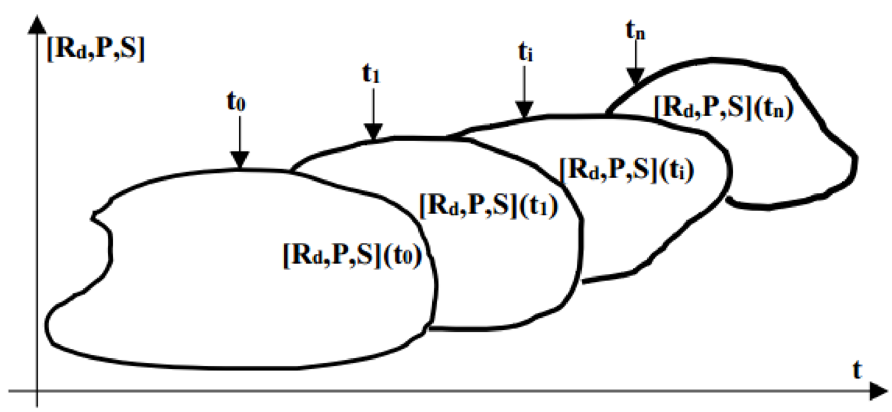


Figure 7. Co-evolution of Design Problems, Design Solutions, and Design Knowledge

(Zeng & Gu, 1999b)

6) Modeling of linguistic information in design-Recursive Object Model (ROM)

The information can be represented in many ways throughout the engineering design process. The most commons ones include: verbal statements, engineering drawings, graphic models, spreadsheets, etc. (G. F. Smith & Browne, 1993). (See Figure 8)

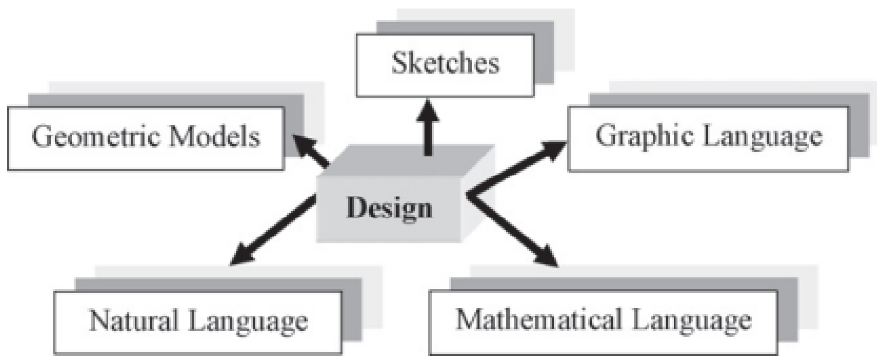


Figure 8. Representations for Describing Design Information (Zeng, 2008)

The EBD proposes a graphic language-ROM to represent natural language used in design. The natural language containing information is transformed into two types of graphic symbols. The first type of symbols stand for the type of objects, either a single objects or a compound of objects together been treated as a single object. The other type of graphic symbols stands for the relationships between objects. In EBD, three types of relationships among the words are identified: constraint relationship, meaning one object is used to describe, limit or particularize the other one; connection relationship, meaning the object is used to connect two other words together, to name a few, “and” “as well as” ; predict relationship, meaning that one object has an act on another one. The five symbols are summarized in Table 1

Table 1. Elements of Recursive Model (ROM) (Zeng, 2008)

Type		**Graphic Representation**	**Definition**
Object	Object	O	Everything in the universe is an object.
	Compound Object	O	It is an object that includes at least two other objects in it.
Relations	Constraint	●——→	It is a descriptive, limiting, or particularizing relation of one object to another.
	Connection	- - - ι - - >	It is to connect two objects that do not constrain each other.
	Predicate	—— ρ ——→	It describes an act of an object on another or that describes the states of an object.

A few examples are listed below:

Example 1: "The tool rivets brake lining onto brake shoes."

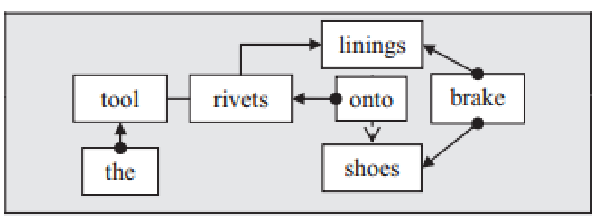


Figure 9. Sample ROM 1

Example 2: "Transportation is to move an object from one location to another."

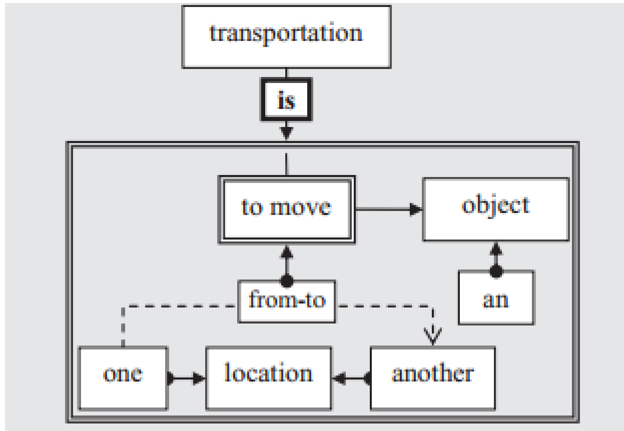


Figure 10. Sample ROM 2

The ROM was originally proposed to deal with linguistic information. It has been extended to process other types of design information as well. ROM can be understood as a representation of the environment structure. More explicit explanation and samples of ROM can be found from (Zeng, 2008)

7) Design System

A product is an object in nature created by human beings and the environment of a product is the collection of all objects in nature except for the product itself. Mathematically, Nature can be seen as a union of product (denoted by S) and its environment (denoted by E). Similarly, a design system is made up of product structure the environment structure, and the mutual relations between the product and the environment. If an engineering system is denoted by $\oplus\Omega$, we have:

$$\oplus\Omega = \oplus(E \cup \quad (5)$$

It can also be represented as:

$$\oplus\Omega = (\oplus E) \cup \qquad \cup \qquad \cup \tag{6}$$

Figure 11 below symbolically illustrates the design system.

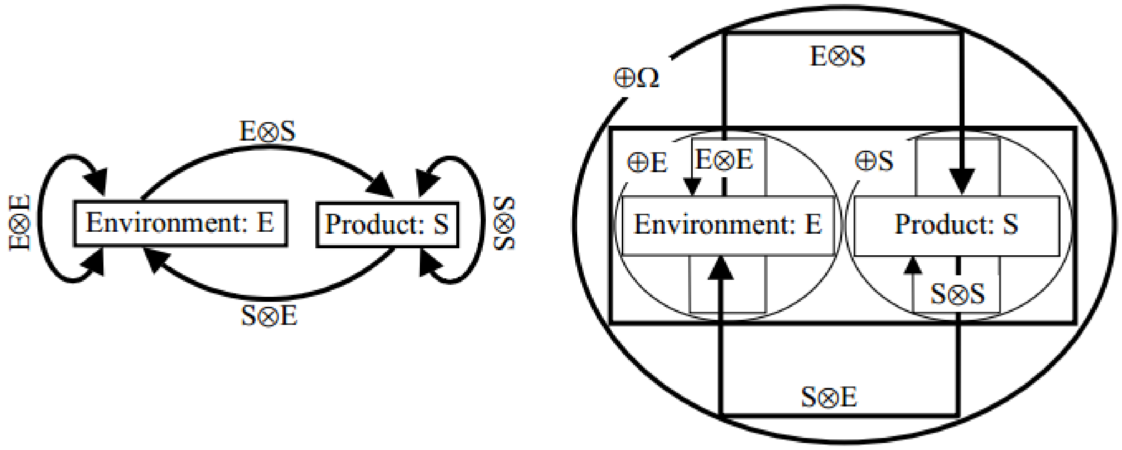


Figure 11. Design System (Zeng, 2002)

8) The concept of “boundary” in a design system

A system always has a boundary and the design system in EBD Theory is not an exception. In EBD, the boundary of a design system is denoted by B, representing the collection of interactions between a product and its environment. Mathematically it can be expressed as:

$$B = (E \otimes S) \cup \tag{7}$$

The boundary of a design system is classified into three types. One is the structure boundary (denoted by B^s, i.e. the shared physical structure between a product and its environment; One is the action boundary (denoted by B^a), i.e. the action the environment imposes on the product, which derives the third type of boundary, i.e. the reaction of the product to the environment (denoted by B^r)

Therefore, the boundary of a design system can be mathematically represented by:

$$B = B^s \cup \quad \cup \qquad B^s, B^a, B^r \tag{8}$$

The concept of "boundary" sets up the foundation for the next concept in the engineering system: the product performance.

9) Product Performance

Product performance, denoted by P, stands for the relations from actions (A) to the response (R). Actions are relations from the Environment (E) to the product (S). Responses are relations from the product (S) to the environment (E) (Zeng, 2002).

$$\begin{aligned} P &\subseteq A \otimes R \\ A &\subseteq E \otimes S \\ R &\subseteq S \otimes E \end{aligned} \tag{9}$$

Since both the product and the environment are treated as objects and are formed with multiple sub-objects, Equation 9 can be refined to:

$$\begin{aligned} A &\subseteq (\bigcup_{k=1}^{n} \qquad \bigcup_{l=1}^{m} \\ R &\subseteq (\bigcup_{l=1}^{m} \qquad \bigcup_{k=1}^{n} \end{aligned} \tag{10}$$

In a product, any of its components are subject to the actions from components that connect to it. As a result, the state of the components may change and reactions may be derived. Figure 12 below shows the performance pattern of a product. The actions (denoted by k) and the reactions (denoted by j) constitute the actions imposed on a component (denoted by i) and the responses of an action are reaction (k), action (j) and state of change (i).

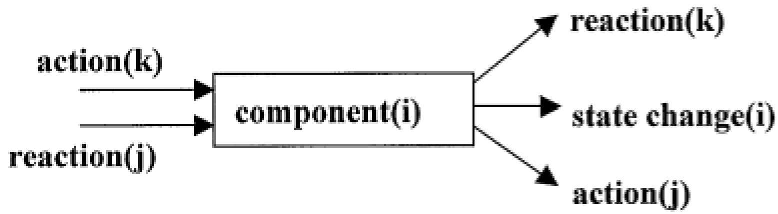


Figure 12. Typical Constituent of Performance Network of Components (Zeng & Gu, 1999b)

The performance of each component within a product forms the performance network, as shown in Figure 13:

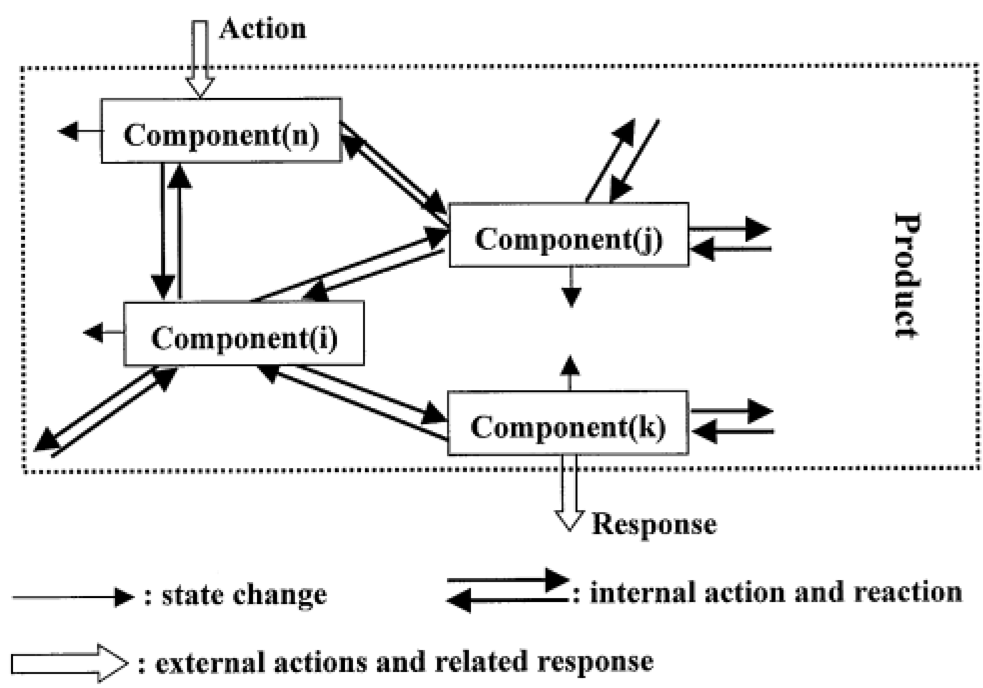


Figure 13. Performance Network of the Components in a Product (Zeng & Gu, 1999a)

4. The Framework of Using EBD to Develop KPIs for a Department

4.1 Introduction

In this section, developing KPIs for a department is treated as a design problem. The EBD methodology is adopted to resolve this design problem. In light of the guidance of EBD, eight steps, including identify the environment, analyze the environment, form the performance network, prioritize the performances, analyze the product, conflict identification and solution generation, are taken to resolve this design problem. Each step is explicitly explained and in the end, the design solution—a framework to develop KPIs for a department is summarized.

4.2 Step 1 Identify the Environment

The fundamental concept of the EBD theory is that a design comes from the environment. Anything but the product can be treated as environment components. However, at the beginning stage of a design, the product boundary is unknown because the product has not yet been designed. It is unrealistic to explicitly define which part falls within the product domain (P) and which part falls into the environment domain (E). Considering that the EBD is a recursive design and the design activities are reiterating by using the "known" to gradually tackle the "unknown", the first-hand design description or requirements can be the starting point. As the design moving forward, the product boundary will be unfolded. For example, in this particular case of designing KPIs for a department, the environment analysis can start from analyzing the sentence of “Design KPIs for a department.”

A ROM diagram can be drawn to more straightforwardly indicate the design problem structure:

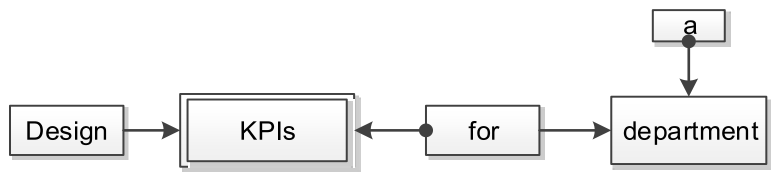


Figure 14. ROM 1

Identify the Environment and Components:

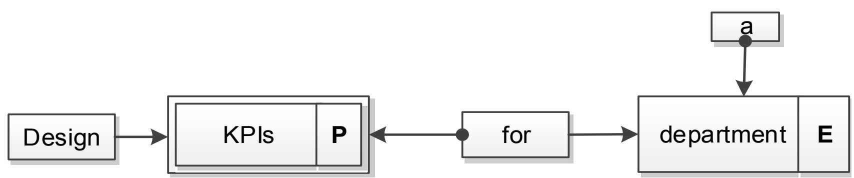


Figure 15. ROM 2

Obviously the environment is “department” and the product is KPIs. i.e., $\oplus E_i$ = department; $\oplus P_i$ = KPIs.

4.3 Step 2 Analyze the Environment

After the environment is defined, the environment needs to be decomposed in order to be further understood. In the EBD, there are a couple of methods to guide the decomposition procedures to ensure that the decomposition is logical and complete. Two of these decomposition methods are the most widely used in the EBD theory. The first one is question generation. Generic questions and domain specific questions are asked in guidance of Wang and Zeng (2009)'s work. The generic questions are the questions that will help designer understand the design problem better while the domain specific questions are the questions that can help the designer collect information that has significant impact to the design problem. The other method is to decompose the environment into human environment, built environment, and nature environment. Human environment refers to the personnel that have direct impacts on the design system; built environment includes every artificial creations of human being and the nature environment refers to all the natural components that are not subject to being controlled by human. These two methods can be tailored or combined together to suit different purposes along the design. In this particular case of designing KPIs, the environment analysis starts from asking generic questions. In light of the (Wang & Zeng, 2009), the 5W1H(who, what, why, where, when, how) questions can be asked:

Table 2. Environment Analysis 5W1H

5W1H	"department"
Who	Who constitutes the environment? Who are the suppliers and customers of this department?
What	What does this department do?
Why	Why does this department do what they are doing?
Where	Where does the department perform their work?
When	When does this department perform their work?
How	How does the department like their work to be done?

All the answers to the questions above form a paragraph or two to describe this department. It can be treated as the definition of this department and a ROM diagram can be formed based on it. However, as all other structural analysis do, the environment analysis in EBD can easily go over-complicated due to the fact that decompositions introduce more and more information into the scope of analysis. It is critical to simplify each step before moving forward. In this particular case of developing KPIs utilizing EBD, before transforming all the answers to the 5W1H questions into ROM diagram, treat each answer as components of the environment. Mathematically, it can be illustrated as:

$$\oplus E = \oplus(\bigcup_{1}^{6} \qquad i = 1, 2, \ldots 6 \tag{11}$$

Table 3. Environment Components

5W1H	E_i
Who	E_1
What	E_2
Why	E_3
Where	E_4
When	E_5
How	E_6

A ROM diagram based on the overall structure as illustrated in Figure 16:

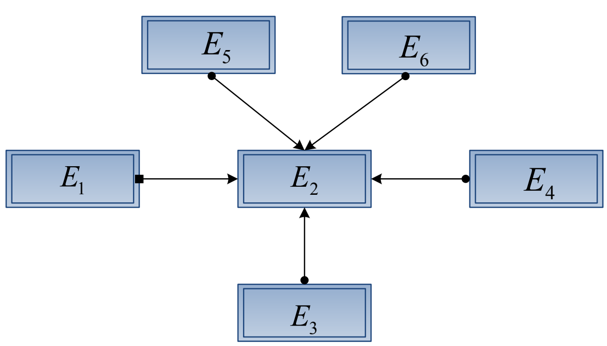


Figure 16. General ROM

According to the EBD theory, a center object the object that "*has the most number of predicate and constrained relations*" and it is often the starting point for the environment analysis. (Wang, Zeng, Chen, & Eberlein, 2013). Based on Figure 16 we can easily identify that E_2 is the center environment component among all the primitive objects from E_1 to E_6 . Therefore E_2 should be analyzed first and in the following analysis, most of the analysis will focus its attention to E_2 .

E_2 is the answer to the question "what does this department do?". In other words, "what processes is this department involved in?" This naturally forms the focus of the next step of developing KPIs: analyzing the business processes and form the performance network

4.4 Step 3 Form the Performance Network

4.4.1 Overview

From the view of the business prospect, an organization, division or department is a complex web of people and functions. Teams and individuals work together. Individuals and teams work together. The department realizes its mission and fulfills its duty through a range of interrelated or parallel processes. The integration level of processes in an organization has been continuously growing in today's society. In the mid-80s, the TQM was popularized and it introduced the concept of continuous improvement of the business processes throughout the organization. A few tools that have long been put on the shelf attracted manager's attention and became popular again. This includes: process mapping, flowcharts, cause-and-effect diagrams and so on. The business re-engineering concept introduced by Michael Hammer in 1990 also highly relies on the process analysis and the quantification of its performance. In the 21st century more and more companies start to realize that process performance is a key factor in high-level decision making and business success. (R. F. Smith, 2007)

From research point of view, researchers have been striving to discover the tangible and intangible benefits of understanding and managing the processes and to seek for more efficient process models as well as the mathematical principles behind them. The pioneers were Skip Ellis, Anatol Holt and Michael Zisman (Ellis, 1979; Scheer, Thomas, & Adam, 2005; Zisman, 1977). The process modeling had been popular during 1970s to 1980s. However, due to the immaturity of the IT community and the fact that the tasks were rather independent from each other than cascaded together with high level of interaction. Thus the concept of process was not emphasized, resulting in the almost-one-decade intermittence of the development in the research field of process modeling. However, towards the mid-1990s, the research academia renewed its interest in process modeling, in light of the popularization of re-engineering (Scheer et al., 2005).

Currently there are a number of process modeling techniques including flowcharts, dataflow diagrams, unified modeling technique (a visual, object-oriented, and multi-purpose modeling language), state charts, queuing network, Markov chains, Process algebra's such as ACP, CCS, CSP and Petri nets. Each of them focuses on different perspectives and can be tailored to suit the user's best interests. Generally, the process flows focus on the following different perspectives: actions and control flow; data and object flow; organizational structure; interaction-centric views on business processes, and system specific process models used for process enactment (Scheer et al., 2005).

However, most of the modeling techniques lack of profound mathematical foundations, which rationalize the modeling process and facilitate the computerization of process modeling. One exception is Petri Net. Petri nets are models developed based on Carl-Adam Petri's Doctoral Thesis published in 1962 (Petri, 1962) and it has undergone continuous developments. A Petri net is a directed graph with two different types of nodes: places, represented by circles and transitions, represented by rectangles or bold bars. Places can carry a token (denoted by a dot) or more than one token. The action of moving a token from a place to a transition or from a transition to a place is represented in arcs. Usually a Petri net is equipped with markings, which is a mapping from the set of places to some domain.

Petri net theory is built based on the Set theory. Mathematically, a Petri net consists of two joint sets: P (places) and T (transitions) and a binary relation $F \subseteq (P \times T) \cup$. The Petri nets can be used to graphically demonstrate the operations and the object state changes, but it does not demonstrate clearly the operators of the operations. It is particularly useful for modeling systems whose behavior is dominated by the flow of information, objects, and etc. and the processes are repeating. For example, Petri nets can be effectively adopted into modeling the manufacturing process of each product. But when it comes to modeling design process, the Petri nets can easily go over-complicated considering each engineering documents can be produced its unique processes with different disciplines involved and different design activities undertaken (Jensen, 1987; Reisig & Rozenberg, 1998; Reisig, Schnupp, & Muchnick, 1992).

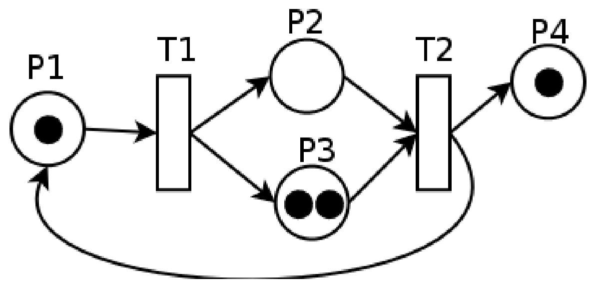


Figure 17. A Typical Petri net

The EBD theory can also be used for process modeling even though it was originally developed to guide the design activities. The concepts and theories stem from the EBD theory along the way of its evolution unlocked a huge potential in its applications in other domains including process modeling. In the following paragraphs, the author will explicit how the concepts of EBD and its tools can be extended into process modeling.

4.4.2 Rationality of EBD in performance network

In the EBD theory, an object is working in its environment. The object is connected to its environment through actions and responses, as is shown in the bellowing Figure 18.

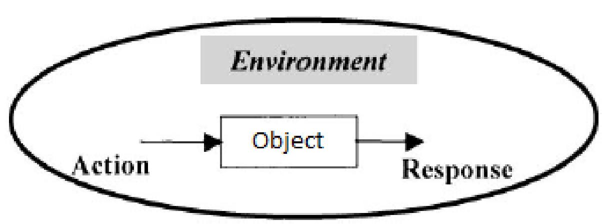


Figure 18. Product Environment

The environment imposes an action or actions on the object and the object responds to its environment. Therefore, an action-response pattern is illustrated as below:

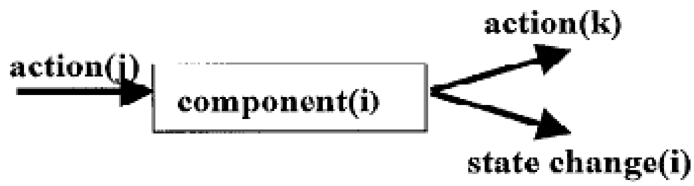


Figure 19. Component Performance (Zeng & Gu, 1999b)

Mathematically, for each business process, the product of the environment can be treated as an object O. In the processes of designing, the products, however, in most cases are design documents. If we denote the design system by Ω, the structure of the design system can be denoted by $\oplus\Omega$. The design system contains the Environment elements and the products. Hence,

$$\oplus\Omega = \oplus(E \cup O) \tag{12}$$

Equation 12 can be expanded into equation 13:

$$\oplus\Omega = E \cup O \cup (E \otimes O) \cup (O \otimes E) \cup (O \otimes O) \cup (E \otimes E) \tag{13}$$

The relation in equation 13 can be divided into following three groups. These three groups can represent a typical set of elements in a design process.

1. E and O

2. $(E \otimes O)$ and $(O \otimes E)$

3. $(O \otimes O)$ and $(E \otimes E)$

(1) The first group is E and O. E represents the environment the product are exposed in while O represents the product, i.e. the design documents.

In EBD, the design specifications (denoted by R^d) for a product are classified into two groups: the structural requirements of the product (denoted by R^s) and the behavioral requirements (denoted by R^p), i.e.:

$$R^d = R^s \cup R^p \tag{14}$$

Similarly, the aforementioned E and O can also be broken into two groups: the structural components and their properties. Mathematically, if using the subscript "s" to represent the structural components and the subscript "p" to represent their properties, we have:

$$E = E^s \cup E^p \tag{15}$$

$$O = O^s \cup O^p \tag{16}$$

On the other side, the EBD also structured the environment into human environment, natural environment and built environment. Similarly, if using the subscript "h" to represent human components, "n" to represent natural components, and "b" to represent built components, we will have the bellowing equation 17 and equation 18:

$$E = E^h \cup E^b \cup E^n \tag{17}$$

$$O = O^h \cup O^b \cup O^n \tag{18}$$

The human environment component E^h of a design processes is any personnel that directly affects the engineering process. It can be the designer, a document distributor, and etc. The built environment E^b can be the facilities being utilized during the design process, to name a few, the computers, the offices, etc. And the natural environment can be the time, the space, the air, the weather, as such. Anything that is not projected to human being's control can be grouped into the E^n

The O^h, O^b and O^n of an object O can be defined in the similar way. However, in this particular case of analyzing the business processes of a department, the object here is often a specific document being processed by this department. It inherently only contains the built components O^b and the sub-objects O^n and O^h can be eliminated. For the sake of simplicity, equation 18 is eliminated from further discussion.

(2) The second group is $(E \otimes O)$ and $(O \otimes E)$. It can be understood as the actions (A) and responses(R) between the design product and its environment. i.e.:

$$A \subseteq E \otimes O \tag{19}$$

$$R \subseteq O \otimes E \tag{20}$$

According to equation 17:

$$A \subseteq (E^h \cup E^b \cup E^n) \otimes O \tag{21}$$

$$\text{i.e.: } A \subseteq (E^h \otimes O) \cup (E^b \otimes O) \cup (E^n \otimes O) \tag{22}$$

$$R \subseteq O \otimes (E^h \cup E^b \cup E^n) \tag{23}$$

$$\text{i.e. : } R \subseteq (O \otimes E^h) \cup (O \otimes E^b) \cup (O \otimes E^n) \tag{24}$$

The $E^h \otimes O$ can be understood as the impacts on the product from human environment, such as the designing, distributions, comments, and etc. $E^b \otimes O$ and

$E^n \otimes O$ stand for the impact of the built environment and the natural environment on the design documents. In the pool of all the impacts imposed on the product O lies the "performances" of a department in an engineering company. If denote the "performance" of the personnel in a department by P, mathematically:

$$P \subseteq (E^h \otimes O) \qquad (25)$$

The responses from the product O to the environment E also contain three parts: $O \otimes E^h$, $O \otimes E^b$ and $O \otimes E^n$, corresponding to the impacts from the product to the human environment, built environment and natural environment. For example, $O \otimes E^h$ can be "changing people's understanding of the product", "leading to different reactions from people" and etc.; the $O \otimes E^b$ can be occupying more computer storage space, consume paper as such. The $O \otimes E^h$ and $O \otimes E^b$ are really not significant in the big picture of the process analysis, considering that the product here is a document whose ultimate purpose is to deliver information instead of any physical motions. In many other cases, the responses of the product will need to be considered. For example, in a process of manufacturing a motor, if the operator may choose different wire materials and this action will lead to different amount of electricity consumed, the heat exhausted by the motor, and etc.

(3) The third group is $(O \otimes O)$ and $(E \otimes E)$. As is shown in Figure 19, an action or actions imposing from the environment can trigger responses from the object; but the object and environment themselves will also have stage changes in response to the actions. The $(O \otimes O)$ can be understood as the state changes of the object product and $(E \otimes E)$ as the state changes of the environment.

The state change is the primary goal of design processes. In the design processes, the state change of a product can be the transition of a document from has not been reviewed to been reviewed, or a document that has been reviewed being updated into a new version, or even a document that did not exist being created, as such.

The stage changes of an object always come hand-in-hand with the environment state changes, i.e. the changes in the occupation of the space, the time spent, or the natural resources consumed, etc.

The environment state change $(E \otimes E)$ can be perceived as the cost of the state changes of the product: $(O \otimes O)$. This once again corroborated one of EBD's core concepts: "*The design comes from the environment*."

Denote the desired state change of the product (the difference between O_i and O_{i-1}) as o_i, i.e.:

$$o_i = O_i - O_{i-1} \tag{26}$$

Denote the desired state change of the environment (the difference between E_i and E_{i-1}) as e_i, i.e.:

$$e_i = E_i - E_{i-1} \tag{27}$$

The desired environment state change is a function of the desired product state change:

$$e_i = f(o_i) \quad (28)$$

However, the desired state changes may not be perfectly achieved. In order to differentiate the real state changes from the desired state changes, apostrophes are used to represent the actual state changes. Therefore, the actual state change of the object can be demonstrated as the follow:

$$o_i^{'} = O_i^{'} - O_{i-1} \quad (29)$$

The actual state change of the environment is:

$$e_i^{'} = E_i^{'} - E_{i-1} \quad (30)$$

The actual environment state change is a function of the actual object state change:

$$e_i^{'} = f(o_i^{'}) \quad (31)$$

Denote the difference between the actual state change and the desired state change of the product by δ_{oi}; denote difference between the actual state change and the desired state change of the environment by δ_{ei}, we have:

$$\delta_{oi} = o_i^{'} - o_i \quad (32)$$

$$\delta_{ei} = o_e^{'} - o_e \quad (33)$$

δ_{oi} and δ_{ei} can be a base on which the quality of the "performance" of a personnel or department being justified. If a document in an engineering department has achieved the state change exactly the same as desired, i.e. $\delta_{oi} = 0$, the personnel or the department has performed the work as expected. If $\delta_{oi} = 0$ and $\delta_{ei} = 0$ in the same time, i.e. the personnel or the department has performed the work excellently with the desired quality achieve and minimum resources consumed. If $\delta_{oi} \neq 0$, it means that there are deviations between the actual performance and the desired one. In other words, there is a defect or defects in the performance.

Based on the above understanding of equation 13, in developing KPIs for a department, three parts should be paid extra attention: the actions imposed on the process product ($E^h \otimes O$), the state change of the products $(O \otimes O)$ and the state change of the environment $(E \otimes E)$, corresponding to the "performance" of the department personnel, the quality of the document and the resources consumed in this engineering process.

4.4.3 ROM in performance network

There is no need to argue that the two-dimensioned graphical language has significant advantages in more clear and specified communications over the one-dimensioned textual languages. The ROM diagram in EBD is a graphic language developed based on the axiomatic theory. It has a profound mathematical foundation and have been testified by enumeration and case studies (Sun, Zeng, & Liu, 2011; Sun, Zeng, & Zhou, 2011; Tan, Milhim, Chen, Schiffauerova, & Zeng, 2011; Zeng, 2008). The ROM includes five symbols to represent object, compound object, constraint relation, predicative relation and connection relation.

Although the primary purpose of the ROM diagram is to represent the linguistic information appearing in the design processes. It can also be extended to other usage, for example, process work flow.

While all the processes have inputs and outputs as illustrated in Figure 20. A process can be broken into actions cascaded together and each action can be intuitively illustrated by a ROM model in Figure 21:

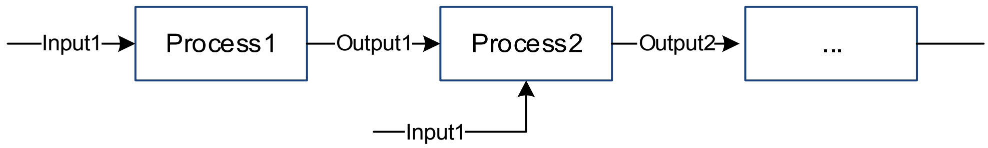


Figure 20. Process Model

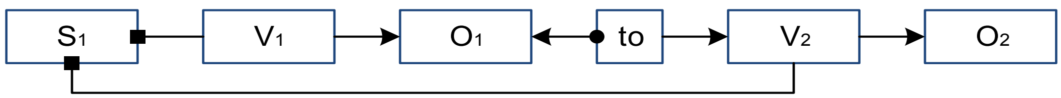


Figure 21. ROM Performance Model

S_1 represents the subject of actions V_1 and V_2. O_1 is the input of the action and O_2 is the output. Perhaps the best way to explain is to give an example:

"Engineers review the documents to add comments"

S_1 = "Engineers"

V_1 = "Review"

O_1 = "documents"

V_2 = "add"

O_2 = "comments"

Although each activity in a process can be described by sentences of different structures, it can eventually be transformed into a model that is similar as Figure 21, considering that an action always have a subject (S), an action (V_1), an action receiver (O_1) and a purpose (V_2 and O_2).

Several or a number of actions being cascaded or parallel to each other forms a process and several or a number of process being cascaded or parallel to each other forms a system, as illustrated in the Figure 22:

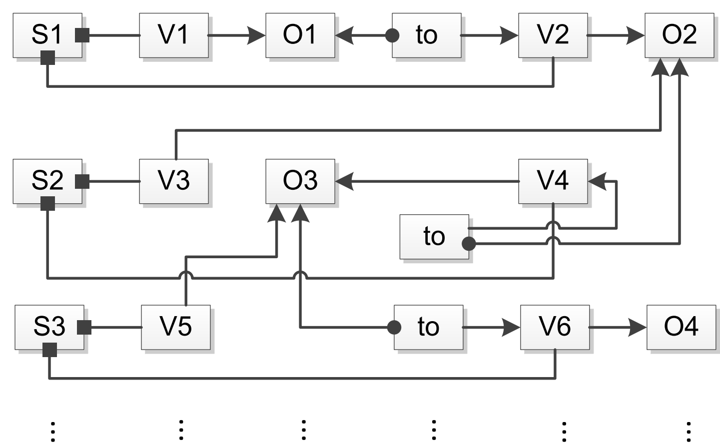


Figure 22. Performance Network Model

4.4.4 Performance network standardization

All the “V” in the Figure 22 can be treated as performances of the subject. Mathematically, the “S” in the ROM is correspondent to E^h ; the “O” in the ROM is corresponding to O; the “V” is corresponding to $E^h \otimes O$ and the state change of O, for example, from O_1 to O_2 is corresponding to $O \otimes O$.

In this particular application of developing KPIs for a department, the "V" s in the ROM diagram are the focus of the study. They should be extracted from the ROM, as illustrated in Figure 23.

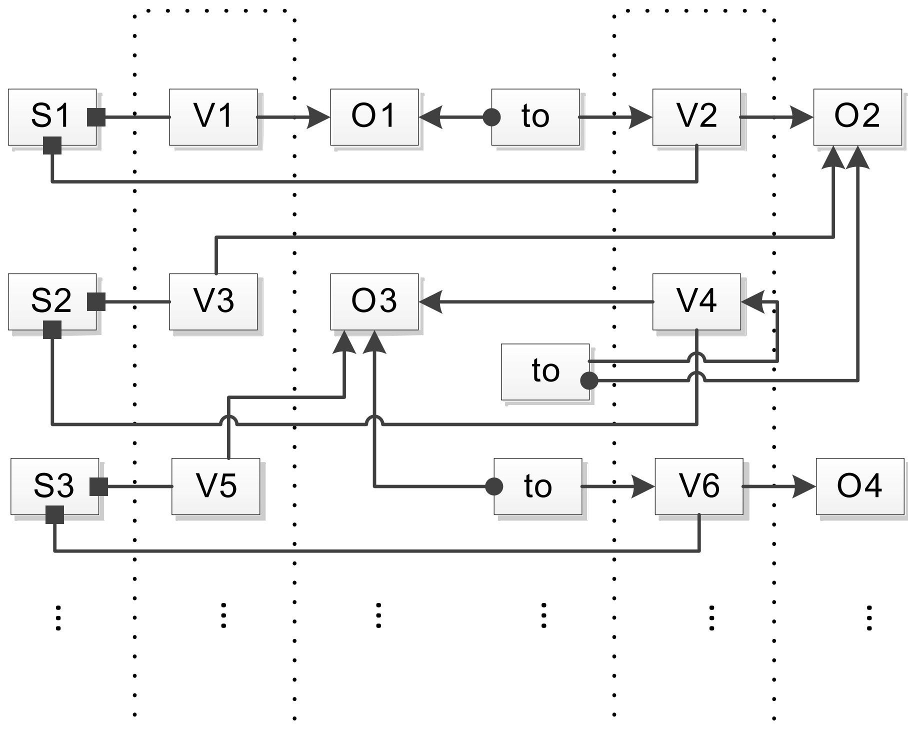


Figure 23. Identify the Performances

4.5 Step 4 Prioritize the Performances

After all the performances have been identified, the next step will be prioritizing them and finding the "key" ones, i.e. finding the "key performance". But on what base are the priorities justified? In the management world, the common methods of developing KPIs are Business Scorecards and Six Sigma. However, neither of these two methods has addressed how to prioritize the performance measurements. The Business Scorecards, for example, is inherently a top-down method. It starts from analyzing the business strategies from four aspects: financial, customer, internal business process and learning and growth, and then flows down through the organizations. Ideally, each department is expected to refer to the Business Scorecards of the overall business as a whole and develop its own Business Scorecards that suit its business level. This means, the lower level the organization goes, the bigger the pool of performance measure grows. In the end, the performance measurement goes so far from the strategies that its purpose is lost (R. Kaplan et al., 1996; R. S. Kaplan & Norton, 2001), let alone to prioritize the performance measurements. Some other methods, instead of analyzing from four perspectives, only consider financial benefits in order to simplify the process of developing KPIs. But simplicity does not make it clearer of how each measurement contributes to business benefits (Goldratt, Cox, & Whitford, 1992). More specifically, for example, in the engineering quality management academia, researchers and engineers have been exploring bottom-up methods to figure out how each aspect of engineering performances, such as the communication, information flow, software adoptions and etc. affect the financial benefits. But the majority of the research methods are consensus questionnaire and empirical data analysis, lacking profound theoretical explanations (A. D. Neely, 2002).

The EBD theory possiblizes selecting the "key performances" through both bottom-up and top-down approaches. As stressed in the aforementioned chapter 4.4.2: Rationality of EBD in performance measurement, the environment state change can be a baseline to prioritizing the performances. To avoid the redundancy, the explanation on why the state change of the environment $(E \otimes E)$ is related to selecting the KPIs will not be repeated at this section any more.

How to prioritize the "performances" using EBD? The most intuitive concept of prioritizing is probably to assign values to the "performances". Each "defect" of the performance will cause the correspondent environment state changes that deviate from the desired environment changes and all the downstream "performances" can be affected, in a fashion of chain reactions.

The deviations of performances may cause significant financial losses when the design has been transformed into real equipment but not only staying on the paper. Therefore, the value of each "performance" can be assigned based on the sum of all the environment state change deviations triggered by the downstream activities of this specific "performance". This is the bottom-up approach of selecting the "key" performances using EBD theory.

On the other hand, as an environment component identified at step 1, the "department" will also be analyzed and its mission, accountability and responsibilities will be addressed. The correlation between the mission/accountability/responsibilities and the activities can be studied in selecting the "key" performances.

After the performances being prioritized, those performances of higher priorities are selected as "key performances", denoted by $P_1, P_{2,} P_{3,} \ldots$

4.6 Step 5 Analyze the Product

Following the EBD's guidance, up to this stage, the main environment components identified in step 1 have been analyzed. The product requirements will be analyzed in this step.

The EBD theory has categorized the product requirements (denoted by R^d) into product structural requirements (denoted by R^s) and product functional requirements (denoted by R^p), also known as performance requirements (see Figure 24)

$$R^d = R^s \cup R^p \quad (34)$$

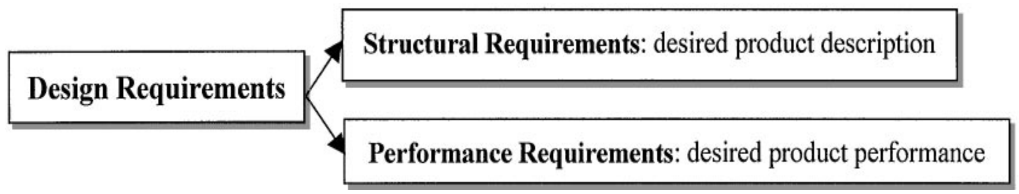


Figure 24. Product Environment

Product structural requirements are constraints on dimensions, shapes, configurations, materials and etc. The performance requirements are the requirements of the action-response modes. For example, a market performance can be that a change of material will change the manufacturing cost (Zeng & Gu, 1999b).

In the focus of this thesis work, the product is KPIs. The structural requirements and the performance requirements will be analyzed in the bellowing section. Referring to the training resource published by the US Energy Department (Group, October 1995), the KPIs projected to be developed should contain three structural parts: the defined unit of measure, “sensors” that gather and record the raw data and the frequency of the measurements and reports. Therefore,

$$R_1^s = \text{"defined units"}$$
$$R_2^s = \text{"'sensors'"}$$
$$R_3^s = \text{"frequency"}$$

In terms of the performance requirements, different applications may have different requirements. Referring to Buchheim (2000)'s work the performance measurement can have the below requirements: Easy to understand; the efforts it takes to collect and use of the data should be minimized; the frequency to collect the data should be appropriate to the nature and the use of the data; the metrics should be measuring results rather than activities; data and measurement system are preferred to already existed; the measurements should directly relate to the customers… These requirements are listed below:

$$R_1^p = \text{"easy to understand"}$$
$$R_2^p = \text{"use in-place data"}$$
$$R_3^p = \text{"use in-place 'sensor'"}$$
$$R_4^p = \text{"reasonable monitoring frequency"}$$
$$R_5^p = \text{"measures directly relate to customers"}$$
$$\ldots$$

Therefore, a pool of the product requirements is formed below:

$$R_1^s,\ R_2^s,\ R_3^s,\ R_1^p,\ R_2^p,\ R_3^p,\ \ldots$$

4.7 Step 6 Conflict Identification

As introduced in the chapter 3, it is one of EBD's core concepts that the conflicts are the driving force of design activities. There are many ways to understand and describe a conflict. But perhaps to put it the most straightforwardly, a conflict is a contradictory relationship between "what we want" and "what we have". In this particular case of developing KPIs for a department, what we want is to "indicate" the "performances" under certain conditions that were described in step 5. i.e. the structural requirements R^s and the performance requirements R^p ; and what we have are the environment components related to the performances, including the performance itself, the built environment components, the human environment components and the nature environment components connected to it, denoted by P_i $E^b_{P_i}$, $E^h_{P_i}$ and $E^n_{P_i}$ respectively. The conflicts may exist between the products requirements (R^s_j, and R^p_j) and the environment components (P_i , $E^b_{P_i}$, $E^h_{P_i}$ and $E^n_{P_i}$); the conflicts may also exist within the product requirements. An example is illustrate the conflict structure in Figure 25.

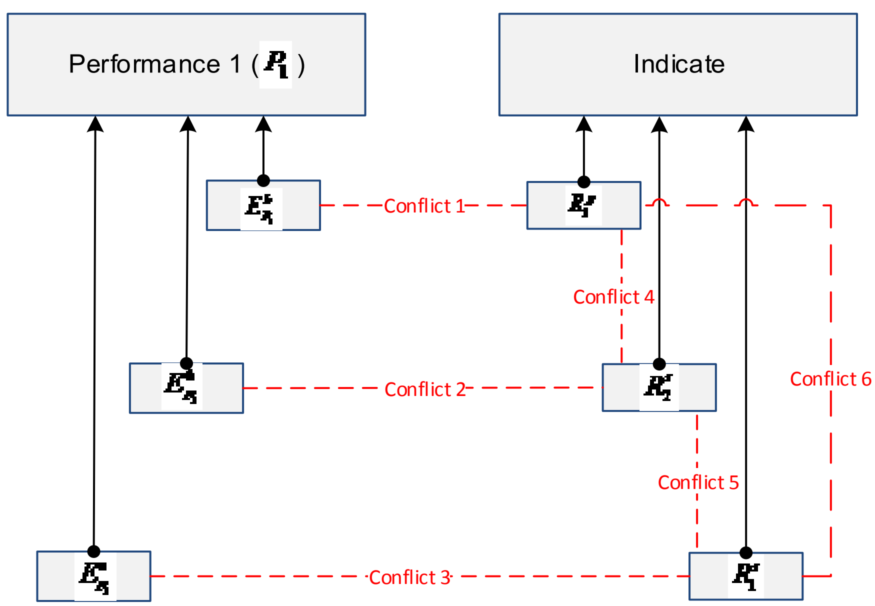


Figure 25. Conflict Structure Example

In Step 4, the target key performances $P_1, P_2, P_3, \ldots$ have already been selected. They are part of the product environment system. More specifically, the key performances are part of the E_2 identified in step 1. Up to this step, the related product environment components can be narrowed down to the key performances and the environment components that are directly connected to them. For example, the actors of the key performance, the action receivers, input resources, and etc.

For each performance P_i , there are built environment components, human environment components and nature environment components connected to it. Denote them by $E^b_{P_i}$, $E^h_{P_i}$ and $E^n_{P_i}$ respectively. Therefore, the relevant environment components pool can be:

$$\begin{array}{llll} P_1, & E^b_{P_1}, & E^h_{P_1}, & E^n_{P_1} \\ P_2, & E^b_{P_2}, & E^h_{P_2}, & E^n_{P_2} \\ P_3, & E^b_{P_3}, & E^h_{P_3}, & E^n_{P_3} \\ & & \cdots & \end{array}$$

In order to guide the analysis and identifying all the potential conflicts in a systematic fashion, a two-dimensioned matrix is built (Table 4). Conflicts can be found between any two items from the product requirements and the product environment components. Conflicts can be denoted by C_i and they are recorded in the matrix (Table 4) if there are any.

Table 4. Conflict Identification Model Matrix

	R_1^s	R_2^s	$\cdots$	R_1^p	R_2^p	$\cdots$	P_1	$E_{P_1}^b$	$E_{P_1}^h$	$E_{P_1}^h$	P_2	$E_{P_2}^b$	$\cdots$
R_1^s	-	C1	$\cdots$										
R_2^s	$\cdots$	-											
$\cdots$			-										
R_1^p				-									
R_2^p					-								
$\cdots$						-							

4.8 Step 7 Solution Generation

Solution generation in EBD has a lot of similarities to the Theory of Inventive Problem Solving (TRIZ) in terms of taking conflicts as design input. However, the limitation of TRIZ is that it is only applicable to resolve physical contradiction but cannot do much to the non-physical contradictions such as the administrative conflicts (Savransky, 2002). The recursive resolution concept in the EBD theory does not have this limitation. It is able to resolve almost any type of conflicts. The underlying concept is that some conflicts can be solved first and the solution of these conflicts can be used as a design input, providing extra information to help tackle the unsolved ones (Zeng, 2011a).

In this specific application of developing KPIs for a department, the product requirements and the conflicts identified in step 6 are the starting point. Wang and Zeng (2009)'s questions asking techniques are once again leveraged in order to further understand the design requirements and the conflicts. For example, for R_1^p , questions such as “What does it mean by ‘easy to understand’” can be asked and the answer can be “being easily demonstrated in the forms or figures and having a proportional relationship between the of performance levels”.

With further understanding of the conflicts by asking questions and answering them, the conflicts can be transformed into ROM diagrams as illustrated in Figure 26 to have a clearer demonstration of the contradictory relationships, facilitating the solution generation process. The case study in the following chapter will demonstrate how textual descriptions of the conflicts are transferred into ROM diagrams.

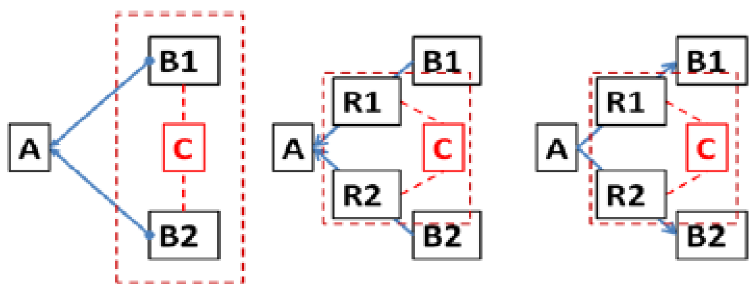


Figure 26. Three Fashions of Conflicts in EBD (Zeng, 2004)

There are three types of conflicts in the EBD theory. The first are the conflicts between any pair of constraints to a common object; the second are the conflicts between any predicate relations from a common object; and the third are the conflicts between any predicate relations to a common object.

After all the conflicts are transferred into ROM diagrams, the analysis will only have to be focused on resolving the contradictive relations. The fully and completely resolutions of the conflicts will naturally lead to the design product: the KPIs for a department.

4.9 Summary

Based on the above analysis, a framework of developing KPIs for a department can be summarized as:

(1). Analyze the environment of this department; understand its mission/accountabilities/responsibilities and identify the related business processes.

(2). Analyze the business processes and transform them into performance net-work.

(3). Find the "performances" based on the performance net-work.

(4). Prioritize the selected performances based on their extent of alignment to the mission of this department, as well as the sum of the downstream "resources" cost by the nonconformance of these performances. Identify the Key Performances.

(5). Analyze the requirements of the performance indicators. The nature of the KPIs and the characters of the KPIs specified by customer, who is going to use the KPIs, can be used as an input in this step. Form the pool of the requirements of KPIs.

(6). Form the environment pool, centering the "key performance".

(7). Identify the conflicts between the elements in step 4 and step 5.

(8). Resolve the conflicts. List the KPIs identified.

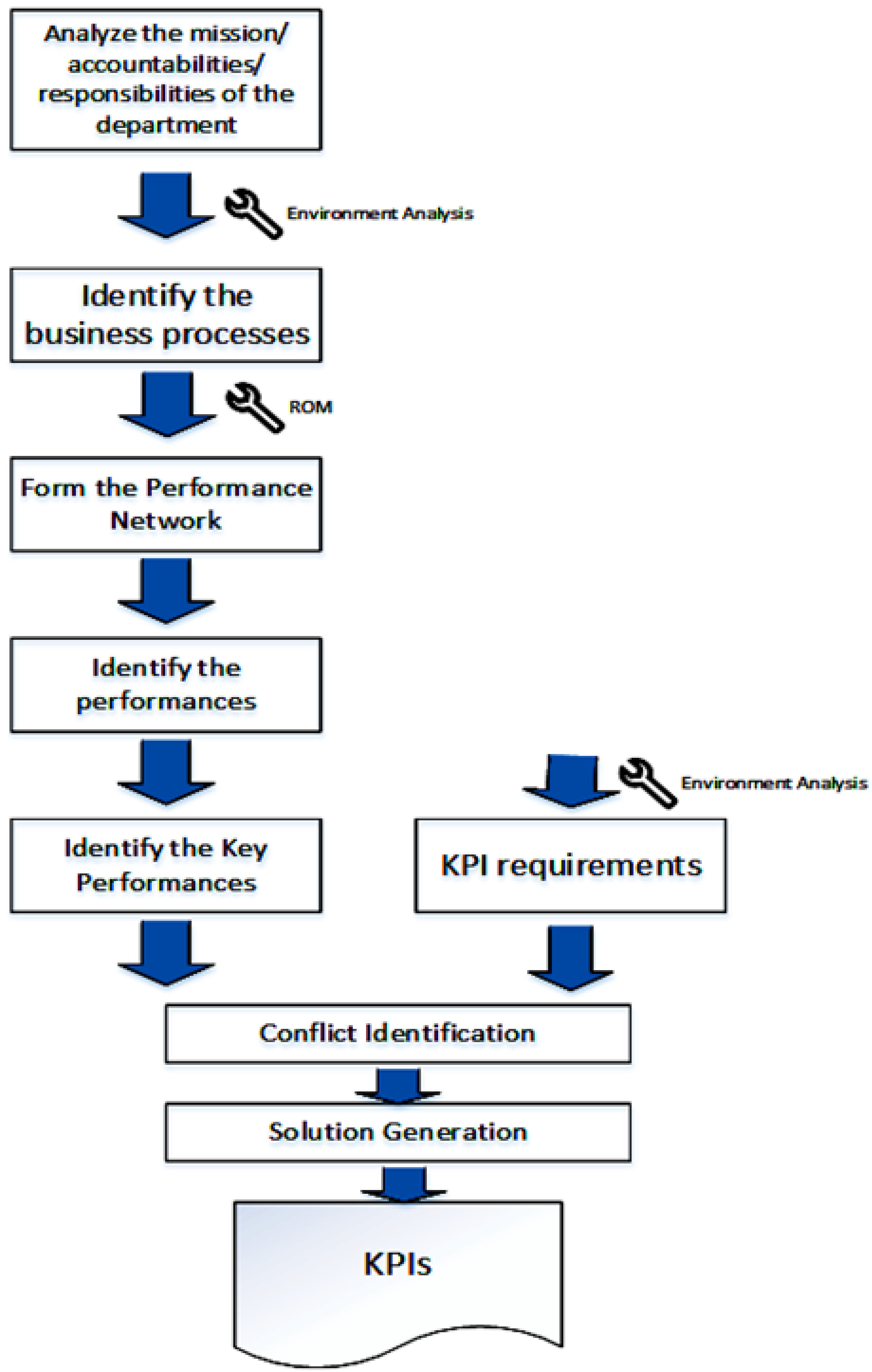


Figure 27. Proposed Framework

5. Case Study

The framework developed in light of the EBD theory in the previous chapter has been applied on a real industrial project to develop KPIs for a central engineering department of an EPC project in the oil and gas Industry. Due to the infringement on intellectual property, the name of the company and department remain anonymous.

Developing KPIs for a department from different industries can be significantly different from one to the other. In order to understand the nature and characteristics of this specific type of project, i.e. the EPC projects, and also to facilitate the environment analysis in the development processes, a background introduction is given in the beginning of this chapter. The definitions of performance measurement in the EPC projects, and the challenges in the EPC projects are discussed in the beginning of this chapter.

The framework proposed in chapter 6 is then tailored and adopted to suit for this specific case study. The procedures of using EBD to develop KPIs contains three major steps. The first step is to find out the "performances" of this department starting from identifying the Environment Product and their relationships based on the design requirements from the customer, i.e. a specific department. ROM can be utilized for the purpose of having a more structural expression of design requirements, facilitating a better and clearer understanding. After the ROM was drawn and the environment, product as well as the interactions between them are identified, a set of questions are asked under the guidance of (Wang & Zeng, 2009) and the ROM diagram is updated to include more information. The critical components are emphasized during the analysis.

Based on the ROM, further analysis is conducted. A performance network is formed and the "performances" are defined in this step. The second step is to prioritize the performances identified in the first step and select the key ones. Two criteria are referred to in order to justify which performances have higher priorities: the cost of non-conformance and the extent of the alignment with the mission of the central engineering department. The final step is to develop the appropriate indicators. Conflicts between the product requirements and the environment components are analyzed and example indicators are proposed.

(Due to the confidentiality concerns and the length of this thesis, only one typical business process has been selected in order to demonstrate the application of using EBD to develop KPIs for the central engineering department of a real industrial project.)

5.1 Background

5.1.1 Definition of Performance Measurement in EPC Projects.

The nature of projects varies from one to another. A project to design a new product can be significantly different from building a refinery complex. The association of Project Management defines a project as: "*a set of inter-related tasks that are undertaken by organization to meet defined objectives, has an agreed start and finish time, is constrained by cost and [that] has specified performance requirements and resource*". The British Standard Guide to Project Management defines that a project as "*a unique set of coordinated activities, with definite starting and finishing points, undertaken by an individual, cost and performance parameter*" (Sandhu & Gunasekaran, 2004). And in a case study conducted by Sandhu and Gunasekaran (2004), a project is defined as: "*a group of inter-linked activities with a starting and finishing point, in which human, financial, and material resources are organized in such a way as to undertake a unique scope of work, of given specification, within constraints of cost and time, and requiring a central intelligence to direct it*."

Specifically, the EPC projects are projects "involving Engineering, Procurements, and Construction, and which involve the installation of product"(Sandhu & Gunasekaran, 2004).

Engineering/Design is defined as "*the process by which the needs, wishes, and desires of an owner or developer are defined, quantified, qualified into clear requirements which will be communicated to the builders or contractors*"(Blanchard, 2004; Yeo & Ning, 2002), while Back and Moreau (2000) gives a more detailed definition: "*the engineering includes all activities required for an overall engineering function, including numerical engineering analysis required to produce design documents as a final product.*" and the engineering processes "*include the efforts of the designers, all necessary disciplines, the owner, and the suppliers that required to finalize the project scope, complete detailed estimates and schedules, complete detailed design deliverables, and prepare work packages for project execution.*"

The engineering /design process usually consists of the following stages (Dettmer, 1997):

- Concept or Feasibility Study, where a business concept and high-level scope are studied

- Design Basis Memorandum (DBM), where the plant capacity, technology selection for key processes, key components/equipment for the facility, as well as preliminary site plan are determined or produced.

- Engineering Design Specification (EDS) or Front End Engineering Design (FEED), where preliminary design and detailed engineering specifications are produced. Some long-lead specialty equipment may have to be ordered during this stage if the project schedule is tight. It is usually near the end of this phase that the project is sanctioned or approved for expenditure.

- Detailed Design is the stage, where detailed design drawings, specifications and documents are produced for fabrication, construction or installation, commissioning, testing and start-up. This phase represents the largest portion of the engineering effort among all the engineering stages.

Due to the fact that the engineering/design is the key process where many key decisions are made, it often has the most significant impact on the project success as a whole(Yeo & Ning, 2002). Therefore, high engineering quality is critical to the business success and tools such as KPIs can be utilized in the engineering management processes in order to ensure high engineering quality is achieved.

5.1.2 Challenges in EPC Projects

Despite the fact that the industry has been actively addressing the importance and methods of measuring the performance measurement in construction field, particularly on construction productivities (Portas & AbouRizk, 1997; Sanders & Thomas, 1993; Thomas & Napolitan, 1995), very limited efforts have been conducted for the engineering profession, even though the engineering professionals constitute a major driving force for the project success (Georgy et al., 2005a). This may attribute to the growing complexity of the engineering processes, and also the difficulties to develop quantifiable measurements to measure the engineering factors that can often only be depicted in vague linguistic terms.

EPC projects are highly complex and one-of-a-kind projects that involve many contractors and sub-contractors (and their sub-contractors) working together to meet the requirements of a particular customer. Hundreds even thousands of activities inter-depend on each other and intricately connect together. The upstream can affect the downstream activities but the downstream often also in turn affect the upstream activities in a fashion addressed in Figure 28:

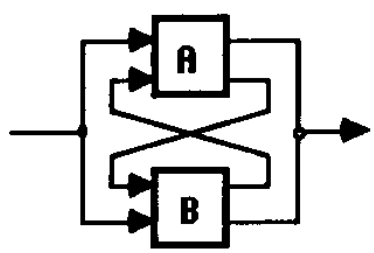


Figure 28. Inter-dependent Activities (coupled) (Austin, Baldwin, & Newton, 1994)

An EPC project has a tremendous amount of interfaces to manage. Different parties or individuals work together in two ways: working together to complete a process or one function hand over to next function. It normally is the later one that complicates the processes. Think about a relay race. A team often falls far behind is a result from dropping the baton. Not fast enough normally leads to a small margin of falling behind. It requires synergetic efforts to ensure that hand-overs are going smoothly and rally all parties to work together towards a common goal (R. Kaplan et al., 1996). The huge amount of interfaces forms a challenge of the EPC projects.

Communication during the engineering of EPC projects can be ad-hoc, too. With multiple disciplines: mechanical engineering, piping engineering, construction and civil engineering, electrical engineering, etc. each utilizes their own expertise and tends to focus on their own area. However, the engineering process is not a one-way street. It requires many active interactions to finalize each one single design. Studies show that the engineering personnel constantly have communication difficulties. People in various functional groups possess various information and tend to only look after their own field. (Moreau & Back, 2000; Workman Jr, 1995). More than half of the errors and omissions in construction drawings and specifications can trace back to poor engineering communication between different disciplines (Kartam, 1996).

Even in 21^{st} century, the engineering deliverables still highly rely on the information exchange in paper form, which is error-prone and lacks mobility. In a study conducted by Taylor (1992), it shows 80 per-cent of an engineer's time is spent accessing data in order to start a study in the paper-based design processes. However, fully electronizing is not feasible at the current stage or the recent future either. Considering it requires extremely powerful processers to handle the over-whelming amount of information, which can cost companies a fortune. On the other hand, fully electronizing can diminish some advantages possessed by paper-based design processes. For example most of the drawings require pen-signs, which will unavoidably require paper drawings. In terms of some engineering processes such as squad checks (A squad-check is one term used to identify a collection of multi-discipline personnel responsible for a design. A squad check would be reviewed by the group as a first look at the cohesiveness/completeness of the design prior to a formal design review), engineers are still more comfortable with paper-formed drawings where comments from every other person can be accessed instantly.

5.2 Part 1: Define Performances

Start from the design problem, “Design a Key Performance Indicators (KPI) List for the central engineering department to indicate their performance during Detailed Design phase.”

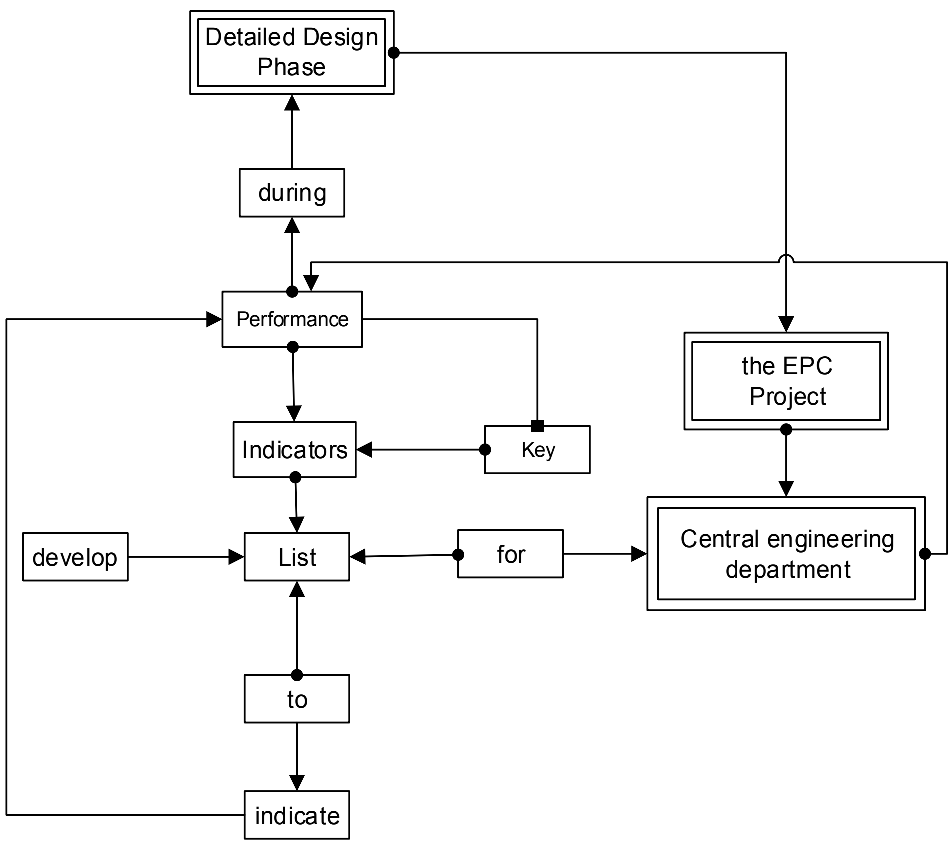


Figure 29. Case Study ROM 1

Identify the environment components (denoted by E in the ROM) and the product (denoted by P in the ROM).

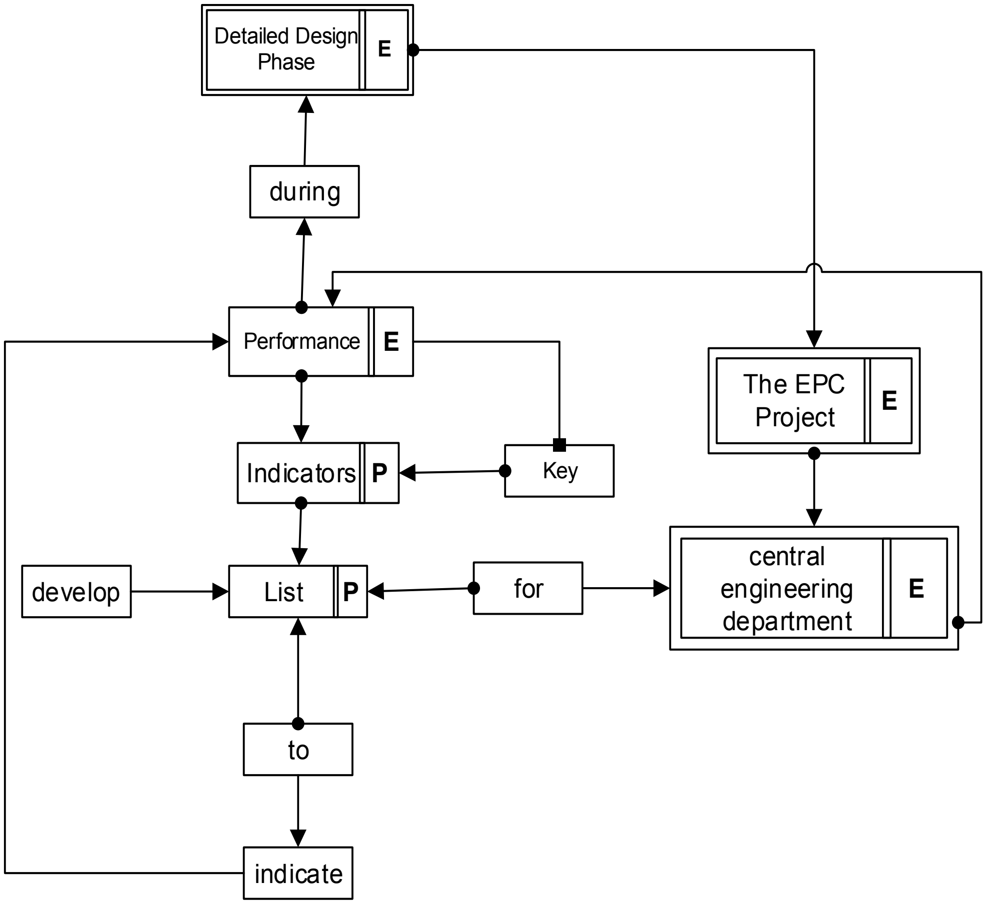


Figure 30. Case Study Environment and Product

Based on this ROM, the following environment components need to be analyzed.

$E_1 =$ "the EPC project"
$E_2 =$ "central engineering department"
$E_3 =$ "detailed design phase"
$E_4 =$ "The EPC project"

The product components, are:

$$P_1 = \text{"list"}$$
$$P_2 = \text{"indicators"}$$

Following (Wang & Zeng, 2009), a list of questions are asked in order to further understand each component of E_1 , E_2 , E_3 , E_4 , P_1 , P_2 . For example, for E_2 , questions such as "What is central engineering department?" can be asked. And the answer can be "Central engineering department interfaces with EPC project functional teams and all project area EP firms to provide discipline based technical support on a continuous basis."

The local ROM is:

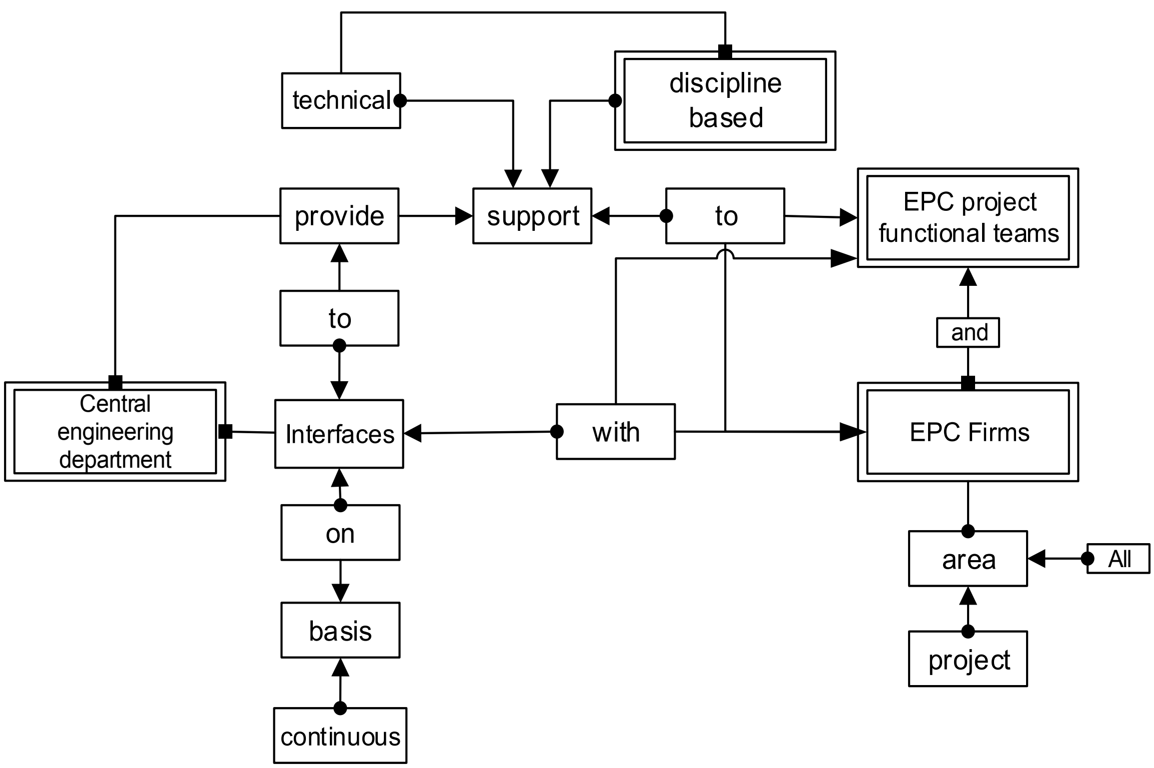


Figure 31. Case Study ROM 2

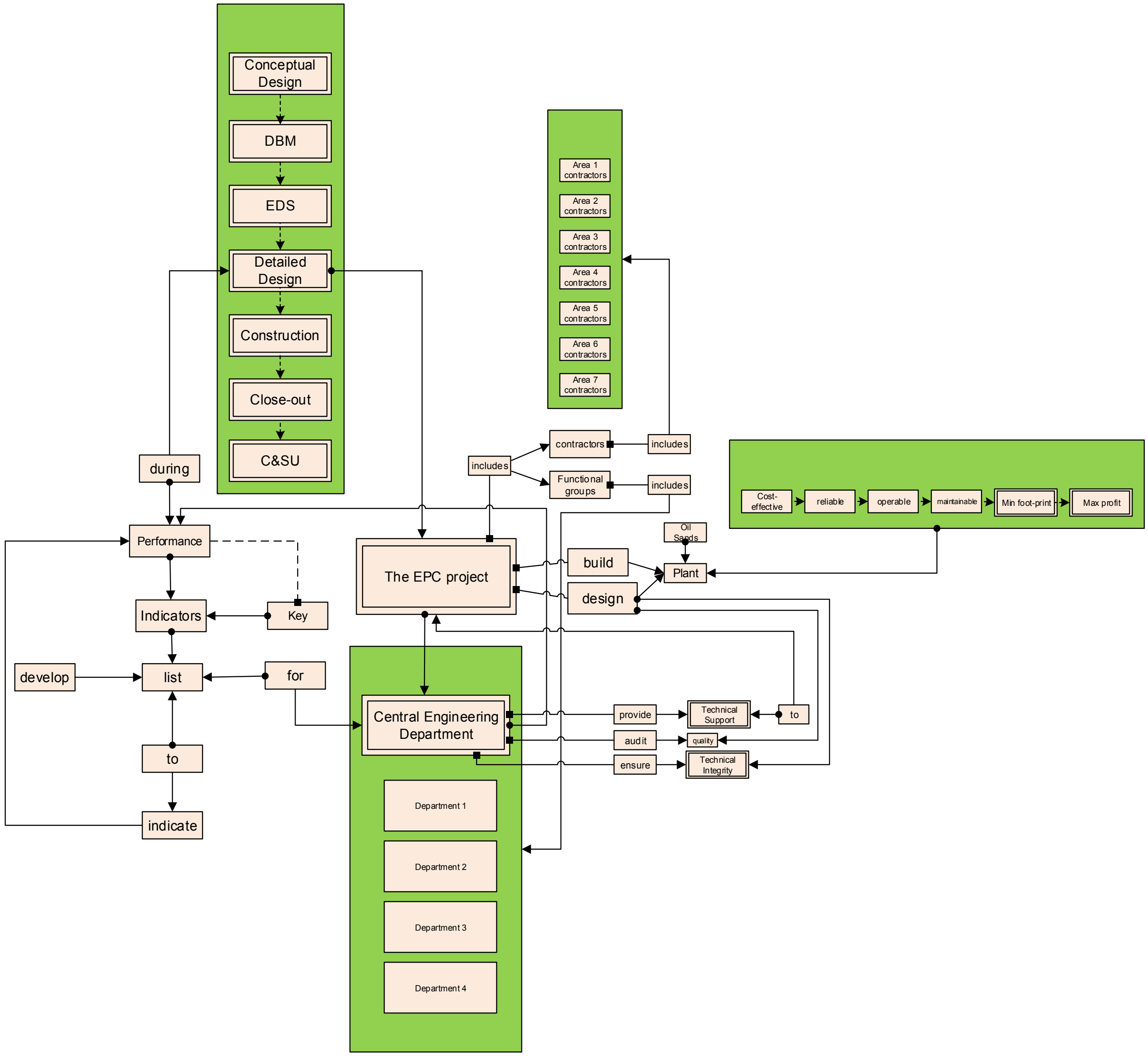


Figure 32. Case Study ROM 3

The business process flows of the central engineering department are identified. One example of its business processes is illustrated in Figure 33:

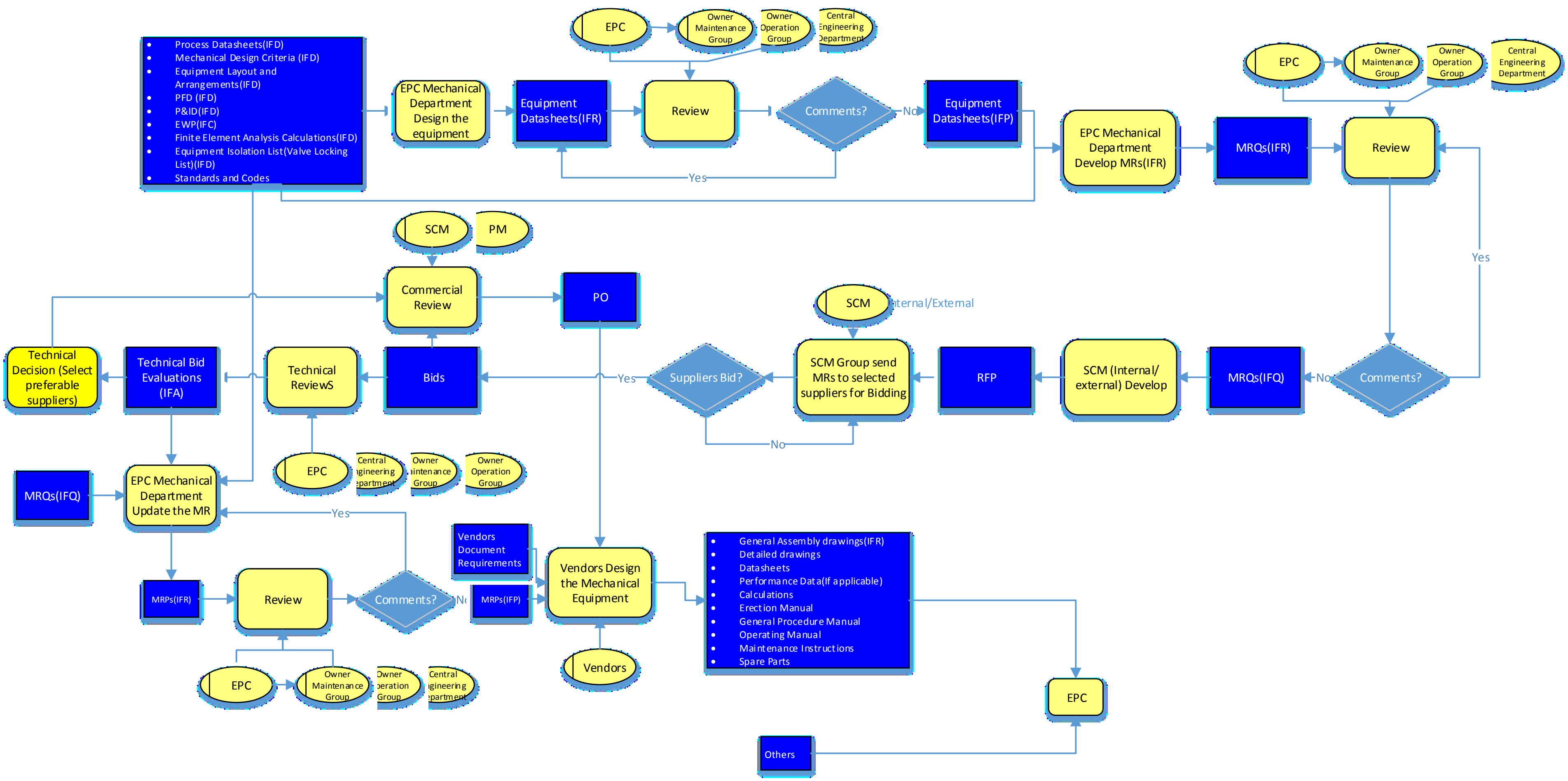


Figure 33. Sample Business Workflow

Transfer this business process into a ROM diagram:

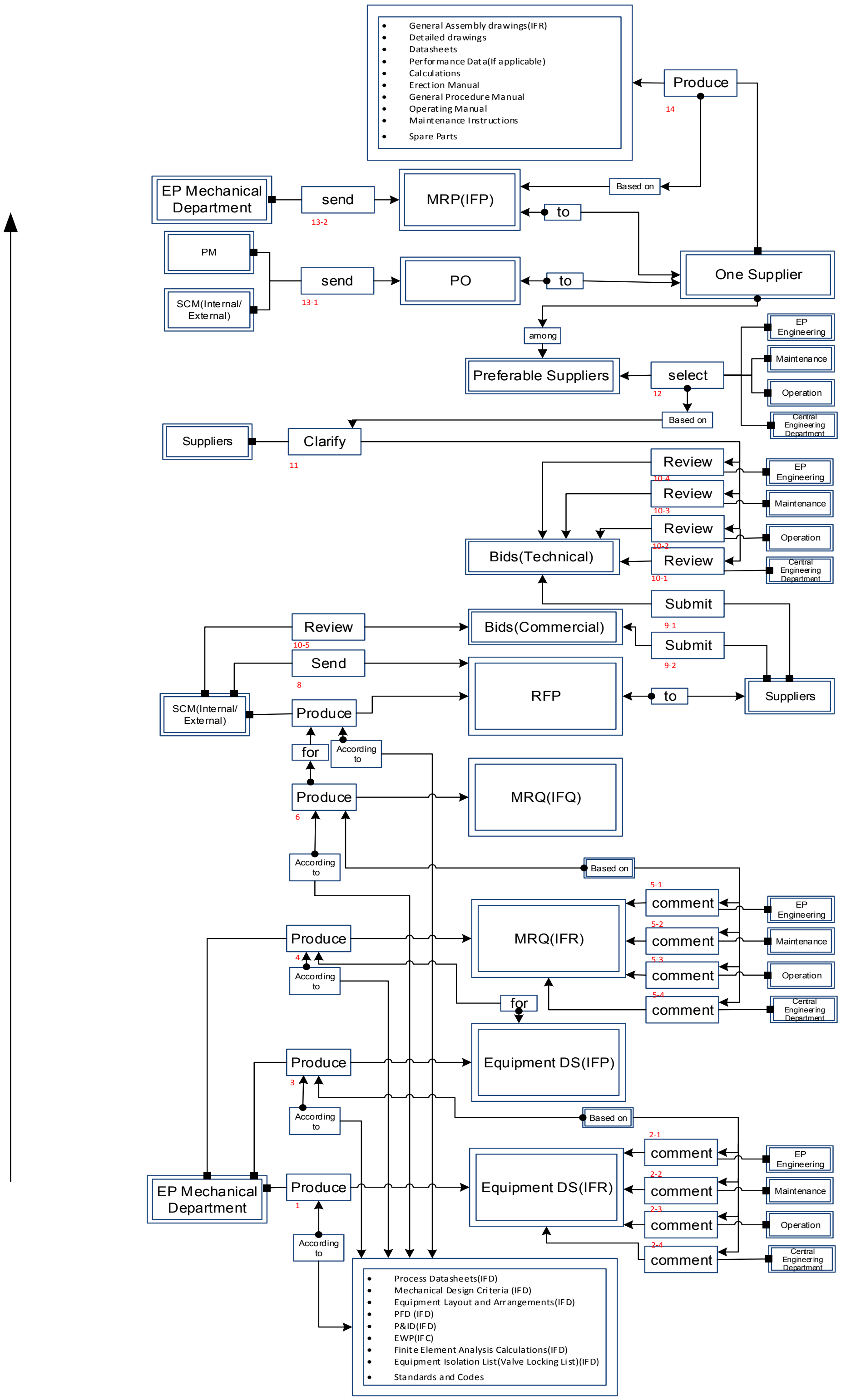


Figure 34. Case Study Performance Network

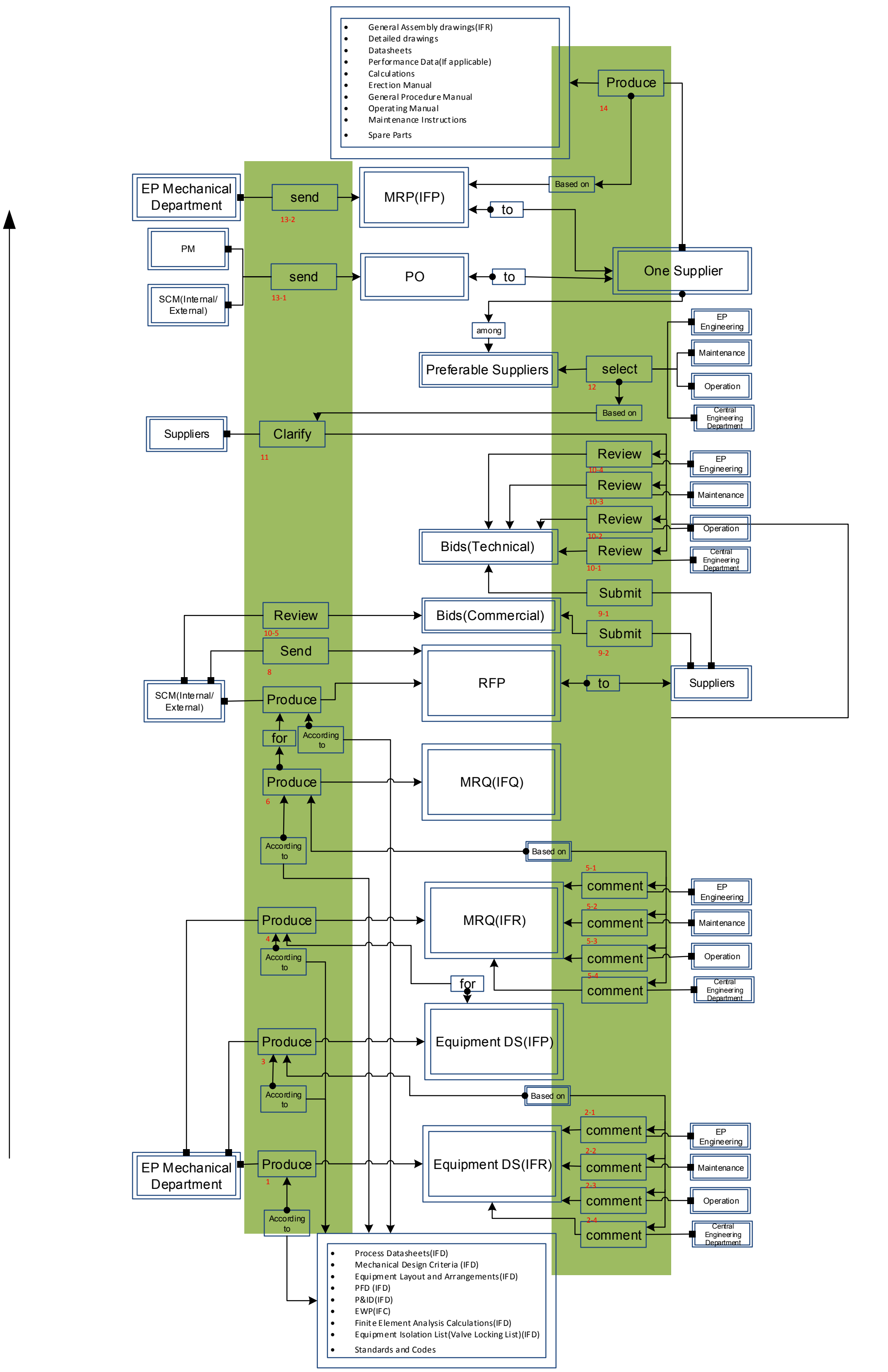


Figure 35. Case Study Performances

The high-lighted are identified as performances. And those related to the central engineering department are of our special interest. They are “comment” and “review”.

Notice that the example given in this case study is only the tip of the iceberg. All the business processes that the central engineering department are involved in should be analyzed and a pool of “performances” will be formed.

5.3 Part 2: Prioritize the Performances

After all the performances are identified, the next step will be prioritizing them. As per addressed in step 3 Form the Performance Network, the prioritization should be performed according to two criteria: one is the cost of non-conformance; the other one is the extent of alignment with the mission of the central engineering department.

Following the example, in order to prioritize the performances “comment” and “review”, the cost of their non-conformance as well as the extent of the alignment with the mission/accountability/responsibility of the central engineering department will be analyzed. For the cost of non-conformance, the ideal situation will be that both of them can be assigned with an absolute number. For example, if the non-conformance of the “comment” costs the total project X dollars and the non-conformance of the “review” costs the total project Y dollars, then apparently the one with a higher dollar will be of higher priority. However, the reality is that it is almost impossible to assign an absolute value to each activity, considering all the activities are integrated and how each activity contributes to the final outcome is nowhere near to know.

Under such circumstance, engineers and managers' experience can be leveraged. Engineers and managers are asked to prioritize the performances with the aforementioned two criteria bore in mind during the reviewing meetings. For example, in this particular case, "Review" is assigned with higher priority because on one hand, if a comment activity fails, there will be plenty of chances to correct them in the downstream activities. On the other hand, if a comment activity delays, it will not hold back the project schedule because in most cases, if a personnel required to comment on something does not make a comment within the preset timeframe, his/her comments will be automatically taken as "no comments", without causing schedule delays.

In terms of the extent of the alignment with the mission/accountabilities/ responsibilities of the central engineering department, both of "review" and "comment" reveals the mission of the central engineering department, i.e. to interface with the EPC project functional teams and all area EPC firms on a continuous basis in order to provide technical support. Both "review" and "comment" reflects the technical support part. But "review" involves more interfaces considering that in many cases, the reviews are done face-to-face. Also, the "review" reveals more accountabilities of the central engineering department because a review often requires the signatures of the engineers. The aforementioned situation where late responses to the comment requirements taken as "no comments" is not very likely to happen in "review".

5.4 Part 3: Define the Indicators.

After prioritizing the performances in part 2, the indicators of the prioritized performances need to be developed. For example, in part 2, "review" is defined as the more critical performance than “comment”. Therefore, the indicators revealing how effectively and efficiently the “review” is done need to be developed.

The requirements of the indicators are developed through literature reviews and meetings with the engineers from this central engineering department. The requirements are summarized as bellows:

(1). They contain measurements, “sensors” and frequency. (As explained in the Step 5 Analyze the Product in the previous chapter.)

(2). The indicators can not only indicate the current performances of the central engineering department, but can also provide visibility of the future state of the performance.

(3). No extra data collections will be required on top of the existing collected data considering that there is already much data in place.

(4). The performance indicators need to indicate the performance status straightforwardly.

Denote the above four items by R_1, R_2, R_3 and R_4

The Environment component of the performance “review” is:

(1). Central engineering department and several other department perform the review

(2). Reviewing are done through squad checks or face-to-face meetings

(3). The technical integrity, conformance to technical standards, and etc. need to be checked during the review.

(4). The review need to be done in a timely fashion

(5). Concerns raised from the reviewing needs to be communicated effectively.

(6). The date of receiving the review and complete the review, the results of the review, as well as the personnel who conducts the review is recorded.

Denote the above six items by E_1 , E_2 , E_3 , E_4 , E_5 and E_6

Table 5.Case Study Conflict Identification Matrix

	R_1	R_2	R_3	R_4
E_1				C4
E_2	C1			
E_3				
E_4				
E_5			C3	
E_6		C2		

Five conflicts are identified:

(1). Conflict 1 (C1): While some reviewing is done through squad checks and others through face-to-face meetings, should they be measured by the same system or separated systems?

(2). Conflict 2 (C2): The data collected is historical. How can they be used to indicate the predictive status?

(3). Conflict 3 (C3): With the recorded information, it easy to indicate whether the review has been done within the timeframe, it is very hard to justify whether the review is effective or not.

(4). Conflict 4 (C4): With several other departments also conduct the review in the same time as the central engineering does, the final outcome may be a teamwork of all parties, making it challenging to differentiate what are central engineering team's performances and what are others'.

Items (1) to item (4) above generally and literally describe the conflicts. To further understand the identified conflicts C1, C2, C3 and C4, they are also transformed into ROM diagrams as bellows and each of the conflicts was discussed during the reviewing meetings.

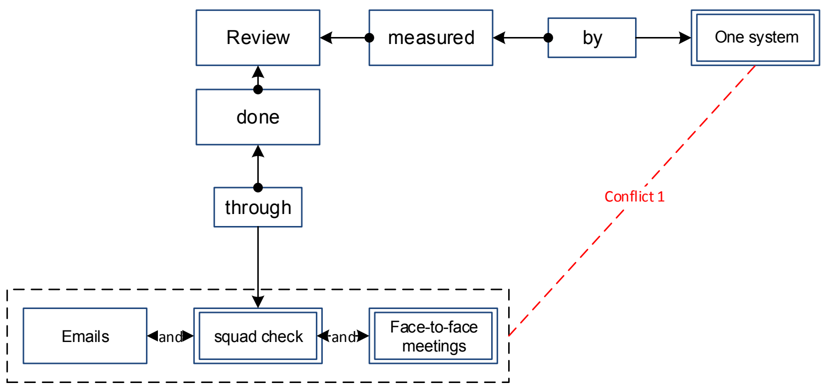


Figure 36. Case Study Conflict 1 (C1)

While there are three different ways of processing the reviews, i.e. through emails, squad checks and face-to-face meetings, they still share some commonality. For example, no matter in which way a review is done, it is only considered completed when the engineers have submitted a written conformation such as an electronic signature, a hand-written signature or an email confirmation. Therefore, measurements that indicated the performance level of a review can be derived from the written confirmations. This can be the solution of the first conflict (C1).

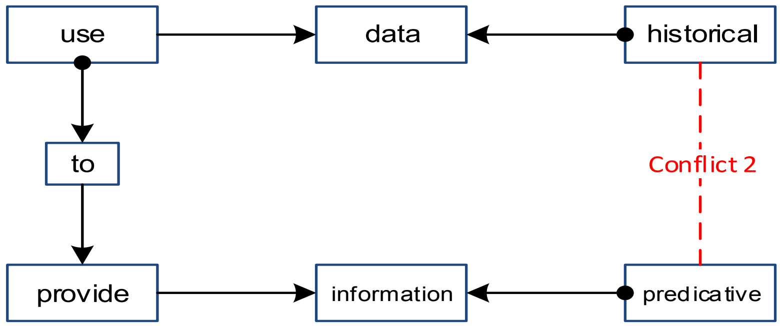


Figure 37. Case Study Conflict 2 (C2)

While the data is intently historical, how do we extract predicative information from the data? By predicative, it means to provide the forward-looking information of the future performance level of the reviews and also the potential impacts to the downstream activities of a review. Perhaps the best way is to look at the tending direction of the performance level over the time. For example, if a personnel in the central engineering department has an increasing amount delayed reviews for the past few weeks, it is very likely that he/she is going to be late in the next month, too.

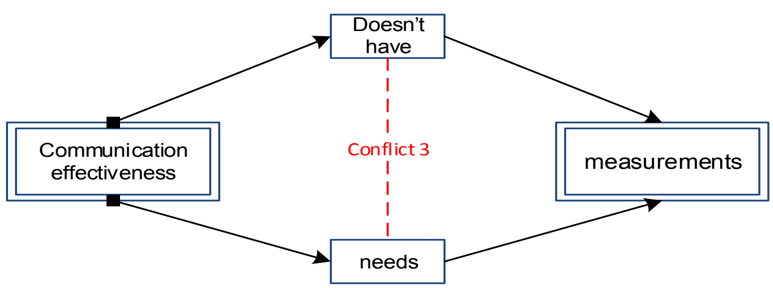


Figure 38. Case Study Conflict 3 (C3)

In order to resolve the Conflict 3, perhaps the first question to ask is: what is an effective communication? The communication effectiveness can be defined as the percentage of information accepted by the receiver over the amount of information a communicator tries to convey. If a concern raised in the review is not communicated effectively, it can be misunderstood even ignored. Therefore, there are two situations that are likely to happen. The first one is that concerns are communicated but are not clear enough. This will cause the downstream activities to request for further clarifications. The other scenario is that the personnel from the central engineering department tries to communicate the concerns, but does not attract enough attention. The concerns ended up being ignored. In this case, a concern is likely to be repeated in the later stages of engineering. For example, the same comment may appear in both the previous and the current reviews in cases where it is not addressed clearly. While bearing in mind that the in-place data is preferred and the requests of further clarifications are not clearly documented, perhaps the best measurement to choose is the ratio of repeated comments over the total amount of comments and its trend over time.

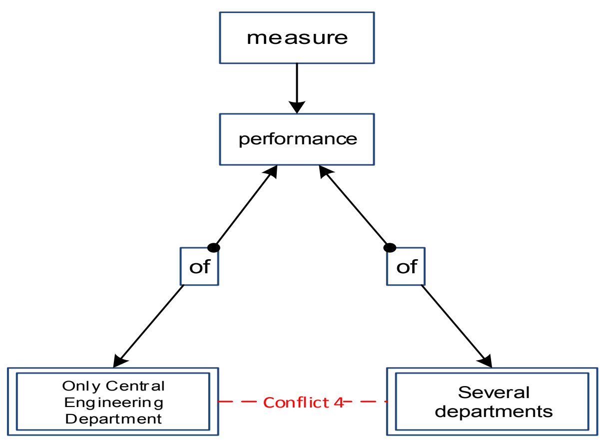


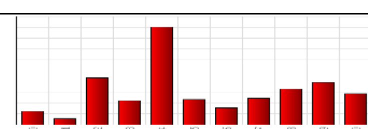
Figure 39. Case Study Conflict 4 (C4)

It is not hard to imagine that the engineering is a combinational effort of different parties and it is not realistic to completely separate the contributions of each department. However, different departments do have their own accountabilities, focuses and emphasis on the engineering outputs. For example, the most important accountabilities of the central engineering department are to make sure the standards are followed and the design integrities are achieved. Therefore, the KPIs for the central engineering department will have to be able to reflect the extent to which the standards are followed and the design integrities are achieved.

After the analysis above, the candidate performance indicators can be: the number of delayed reviews over time, the number of the delayed reviews over the total number of reviews, and its trend over time, the number of repeated comments, the ratio of the number of repeated comments over the total number of comments, as well as its trend over time.

A sample performance check list Table 6 to guide the reviewing activities is also created in order to leverage the indicators in assuring that the central engineering team is performing the reviews in the way it is supposed to.

Table 6. Case Study Sample Performance Checklist

	Name:	Date:
Reviewed conformance to standards?	Yes ☐	No ☐
Reviewed technical integrity?	Yes ☐	No ☐
Delayed?	Yes ☐	No ☐
The ratio of delays in the past	Figure1:	
The ratio of repeated comments over the total number of comments in the past	Figure2:	

6. Conclusion, Discussion, Limitation and Future Work

6.1 Conclusion

This thesis work focuses on proposing a new framework of developing KPIs for a department, utilizing the EBD methodology. A comprehensive literature review on the definitions of KPIs, the Revolution of KPIs, as well as the popular frameworks of developing KPIs were given at the beginning of this thesis. The EBD theory was then innovatively applied by treating "designing KPIs for a department" as a design problem. The traditional procedures of the EBD theory, i.e. environment analysis, conflict analysis and environment analysis were then followed in solving this design problem. A framework of developing the KPIs for a department was then summarized into eight steps followed by a case study on a real industrial project, which testified the applicability of the framework proposed in this thesis.

The proposed framework of developing KPIs for a department is summarized as bellows:

(1). Analyze the environment of this department; understand its mission/accountabilities/responsibilities and identify the related business processes.

(2). Analyze the business processes and transform them into performance net-work.

(3). Find the "performances" based on the performance net-work.

(4). Prioritize the selected performances based on their extent of alignment to the mission of this department, as well as the sum of the downstream "resources" cost by the nonconformance of these performances. Identify the Key Performances.

(5). Analyze the requirements of the performance indicators. The nature of the KPIs and the characters of the KPIs specified by customer, who is going to use the KPIs, can be used as an input in this step. Form the pool of the requirements of KPIs.

(6). Form the environment pool, centering the "key performance".

(7). Identify the conflicts between the elements in step 4 and step 5.

(8). Resolve the conflicts. List the KPIs identified.

The EBD theory was not only used to develop a framework of developing KPIs for a department, it also intuitively defined the performance measurements from EBD's perspective of view. The "performance" can be understood as an action imposed by a human environment component to the products. This action causes the product to responds to the environment; and the states of the environment and the product to change. The performance level of a department was defined according to its impact on the environment. More specifically, the performance level can be justified based on two criteria. One is the cost of the non-conformance of the performances. In this thesis, the cost of non-conformance was defined as the sum of the extra resource consumptions in the downstream activities. The other criteria is the alignment with the mission /accountabilities /responsibilities of the department. The mathematical explanations were also given in this thesis.

One of the most critical tools in the EBD theory—the ROM diagram was also innovatively used to demonstrate the business workflow of a department, unlocking the huge potential of EBD in the applications on process modeling. While maintaining the core concepts and symbols in its traditional applications on modeling textual information, the ROM diagram was used in modeling the business processes at the action level. The information of the actors, input, output, goals, sequences and etc. of the actions of a business process can be easily demonstrated on the ROM diagram.

This thesis also conducted a case study to develop a KPIs list for a central engineering department of an EPC project in the Oil and Gas industry, in order to testify the applicability of the framework developed by using the EBD theory, which makes this thesis also a valuable contribution to the engineering management research. Due to its highly-complex, multi-disciplined, and technical-intensive nature, the engineering management forms a research topic of its own right. Finding effective methodologies to developing KPIs has been one of the most critical ambitions of the engineering management researchers and practitioners. The case study demonstrated how the EBD theory could be tailored and adopted in developing KPIs for an engineering department on an activity-by-activity basis.

6.2 Discussion

The traditional frameworks of developing KPIs such as the Business Scorecards and Six Sigma only provide general guidelines to developing, implementing and maintaining the KPIs. The way of deriving the KPIs are mainly brainstorming, surveys, and consensus meetings, which decide that the KPIs developed through these two methodologies can hardly achieve coherency and consistency. The framework proposed by EBD is developed based on a profound mathematical foundation which has a solid rational in extracting the KPIs. It provides a step-by-step procedures that will walk the developers through the KPI developing process. More specifically, for each step, certain rules are followed based on the EBD theory. For example, the EBD theory provide a comprehensive guide in question asking during the environment analysis and the ROM diagrams are also formed based on certain rules. In the prioritization part, only two criteria are considered. This will inherently decrease the reliance on expertise during the KPI developing processes.

Other current methods to developing KPIs such as combining the process modeling and prioritizing the KPIs through decision making techniques highly rely on the process modeling and subjective judgments of the expertise. Most of the process models can only represent one or several aspects of the business processes and are not particularly designed for developing KPIs. This inherently decides that the information represented in these models are incomplete. On the hand, the models that seeks to represent complete information of the process, for example, the TTL modeling, are expressive, which decide the modeling processes are tedious. It is often too hard to explicitly show the hidden information such as the conflicts, requirements and etc. The ROM diagram in the EBD theory can not only represent the actors, actions, input/output of a process, and the sequence in a straightforward fashion, it can also include the constraint information such as the process requirements whenever and wherever necessary. Using ROM diagram, each action in the business processes are represented in a standardized format (Figure 21).

This will facilitate the computerization of the KPI development, in contrast to the fact that the current methods are mainly conducted manually.

The proposed framework demonstrated how the proposed framework can moderate the above dilemmas in the current methods of developing KPIs.

6.3 Limitations and Future Work

It is commonly argued that the traditional Business Scorecards in developing KPIs lacks of the technical know-how and cannot define the KPIs at a "micro" level. The process of defining the KPIs highly relies on the managers' experience and consensus meetings. The other methodologies of developing KPIs such as the Six Sigma are believed not being able to reflect the business strategies. While the EBD method seeks to leverage the strength of the both the Business Scorecards and the process-oriented approaches by defining the performances in a micro activity-by-activity level, and prioritizing the performances referring to their extent of alignment with the mission /accountabilities/ responsibilities of the department, it still highly relies on the understanding of the business processes. However, in a lot of cases, the business processes of a department are not well documented and it requires a lot of time and energy do define them during the process of developing the KPIs.

On the other hand, how detailed does the business processes analysis need to be? A process can always be broken into micro-processes, actions, even micro-actions. A too general level of process analysis may miss some important information while a too detailed level can be over-whelming. The research academia lacks both the mathematical explanations and empirical studies of on what basis can the level of detail be justified, that can provide sufficient yet not over-whelming information for developing the KPIs. This topic should be on the further research agenda.

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