FUNCTIONAL METRICS IN AXIOMATIC DESIGN

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This work is the fulfillment of a desire. I have always wanted to leave a legacy and contribution. I wanted to advance a field in some way. I feel like I have been able to take axiomatic design, something absolutely beautiful, and make it a little simpler to understand

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Chapter 1: Introduction

1. Introduction

1.1 Objective

The objective of this work is to study, functional metrics (FMs) in Axiomatic Design (Suh 1990), their relationship to each other within the functional domain, and understand ways in which they add value to the design process and the design solution, as well as variables that influence that value.

The scope of this work involves situations in which the top-level metric is related to improving return on investment (ROI). In particular, three design problems will be examined:

(1) Quantifying incoming orders for an engineer to order (ETO) manufacturing company that must prioritize work during over-capacity periods in order to increase ROI

(2) Designing strategies for a football team to increase the probability of winning games.

(3) Managing an ETO company's production processes to better control the outcome of accepted orders and reduce completion date tardiness

This work will consider the design process and design solutions within axiomatic design (AD). ROI might not necessarily be financial. In the design solution that develops strategies for a football team, gain will be measured in points and cost in time.

It should be noted that this work was the result of multiple years. Over those years the term single domain equation (SDE) which is used in this first chapter later became known as parent-child equations in later chapters.

A FM indicates how well a functional requirement (FR) satisfies a customer need. This provides knowledge of whether or not the design parameter (DP) paired with a FR needs to be adjusted to bring the value of the FM to within acceptable tolerance. It is worth noting that FRs at the lower-levels might not address specific CNs but do contribute to satisfying the top-level CN. In axiomatic design, functional metrics relate to each other through SDEs that are present at every level of detail. Unlike a multi-domain equation that provides a functional relation between two different domains, e.g. FR 1.1 = f (DP 1.1), a SDE provides a relation between different levels within a single domain, e.g. FM 1.1 = ((FM 1.1.1 – FM 1.1.2) / FM 1.1.3). Upper-level metrics can be considered dependent variables in the SDE, and their children metrics are the independent variables that combine to equal the higher-level parent's metric.

1.2 Rationale

There are both technical and long-term economic benefits to studying ways to develop functional metrics and relating them to each other, which can be considered two overarching themes within the work to follow, with the former representing the effectiveness of a design process or solution and the latter representing ROI. The effectiveness of a process is measured by how **successfully** the output provides the required value to the customer by meeting customer needs. A path dependency exists between these two themes. However, unlike a traditional coupling in AD, this is parent-to-child dependency and therefore not a violation of axiom 1. ROI, which can be measured as a top-level metric, is dependent on the effectiveness of the design solution, which often takes the form of lower-level metrics. It is unlikely that an ineffective process can maintain a desirable ROI over a long period. Therefore, it is important to measure both effectiveness and ROI as well as to understand the relationship between lower-level and top-level metrics.

This measuring is important because, without metrics, there is no way to objectively determine how effective or efficient a design process or solution is. Lord Kelvin wrote, "If a system or process cannot be measured, then it cannot be objectively improved." A metric is defined as a quantitative measurement of the current state of a process or solution. If improvement can be considered as moving to from one point to another, more desirable defined point in space, a direction for movement cannot be defined without first knowing the current location in space. The use of metrics can identify the current effectiveness and ROI of a design solution, so that the direction the design solution needs to move in can be determined to achieve a goal, meet a benchmark, or continue improvement.

In addition, determining which metrics to use can facilitate communication and consensus. There are situations in which quantification can be a challenge, especially at the lower-levels of a process or solution. For example, the initial top-level customer need for the first design problem to be discussed in this work was to “provide a system for better managing orders.” There can be multiple metrics for measuring the management of orders. Depending on which top-level metric is being measured, it can be a challenge to determine which processes at the lower-level have the highest correlation with improving order management. The metric for success can also vary by perspective. A shop-floor manager’s metric for success might be different from a company shareholder’s metric.

Moreover, current performance measurement systems for measuring financial metrics at the upper levels can negatively affect long-term ROI. "Cost accounting is the number one enemy of productivity"(Goldratt 1983). Using financial metrics to measure the success of a design process or solution has been done for centuries. The problem is that measuring financial metrics alone often focuses on improving short-term ROI in the form or quarterly statements. When short-term ROI is prioritized, it can occur at the cost of effectiveness. A design process or solution should attempt to be as efficient as possible, but not at a cost of value to the customer. “If you want to cut the costs to zero, turn off the lights and send everyone home” (Brown 2015). A system must be effective, otherwise being efficient is a moot point.

Customers will not pay for even the cheapest product if it does not meet their customer needs, and a business that cannot get its customer to buy its products due to loss of value to the customer cannot make a return. Performance metrics (Richardson et al. 1980), called FMs in this work, can facilitate prioritizing effectiveness. SDEs can relate lower-level performance FMs that measure effectiveness to top-level FMs that measure ROI. This can facilitate identifying unintended consequences on effectiveness due to actions that affect ROI. Also, a system prioritizing on short-term ROI might avoid necessary practices like innovation, which can hurt short-term ROI but improve long-term effectiveness and ROI.

Metrics are useful for tracing the root cause of underperformance. When observing top-level financial metrics that are below the desired value, it can be difficult to trace the root cause if nothing at the lower-levels is being measured. Any implemented design process or solution can fail over time due to changes in the surrounding environment, whether it is due to new personnel or processes within the organization or the effect of a competitor’s or supplier’s actions. Measuring FMs on every function at each level and using the relationships among different FMs using SDEs can facilitate tracing the fundamental cause of underperformance.

Using FMs within axiomatic design can facilitate the control of effectiveness and ROI of a design process or solution, particularly for the user. Being able to measure effectiveness and ROI is an important step, but what about controlling the value of the metric? Once the current state is identified, the user must be able to control movement in the direction of the desired goal. Functional metrics can be employed in multiple design frameworks, but axiomatic design was chosen because it provides two axioms, which maximize the probability of a design solution successfully satisfying the top level customer need. Axiom one, the independence axiom, facilitates control of effectiveness and ROI by requiring independence of each function within a design process or solution. This reduces the possibility of unintended consequences on other functions while adjusting a DP in a design process or solution. This prevents waste due to non-value iterations that are put in place to correct such unintended consequences.

FMs for each function at every level can facilitate designing collectively exhaustive mutually exclusive (CEME) processes and solutions within AD, but decomposing a top-level function down to the lowest level can prove difficult, especially for users who are new to AD. CEME is the combination of two concepts. The first, collectively exhaustive (CE), means that everything that needs to be in the design has been included. If some part of the solution that affects FR 0 is not included in the system and therefore is not being controlled, then the system cannot be fully in control. The second, mutually exclusive (ME), means that there is no overlap of the functions, which causes coupling, a violation of axiom one, and thereby reduces the level of control on the system (Brown 2011). An illustration of CEME outside of axiomatic design occurs when creating free body diagrams in Newtonian mechanics. All the forces are accounted for and then decomposed into the x, y, and z components (Brown 2006). Experienced users have suggested that using thematic decomposition (Dickinson and Brown 2009) can facilitate CEME design solutions. However, unless this theme is quantitative, there is no measurable justification to determining whether or not every function that affects the top-level function has been accounted for. When decomposing a system using FMs, SDEs identify which children metrics should be present for a CEME solution and, therefore, which functions must be controlled within the design. This can also help determine the parts of a system that should be removed because they do not have an effect on the top-level metric. AD users of all skill levels could design CEME solutions that provide control of effectiveness and ROI with fewer design iterations. FMs and SDEs provide a quantitative theme for the next level of decomposition and a quantifiable justification for claiming CEME.

Having a metric for each FR when decomposing a design solution could be a corollary that would enable users of axiomatic design to improve their designs. Suh (2001) defines many corollaries that follow from axioms and other propositions that have been proven. An example of an existing corollary would minimize the number of FRs and constraints (Suh 1990). Decomposing with metrics could be a corollary for determining the necessary number of children FRs, based on the number of variables in the parent FR's related SDE. Suh (2001) used metrics for determining the FRs and DPs in his designs, even though children metrics did not always combine to equal parent metrics. For example, his faucet design controls flow and temperature with a metric for measuring each. However, there is no higher-level metric that they combine to equal. Many published decompositions since then have discontinued this use of metrics. Suh did not use the word FM, however his decomposition of a parent FR was similar to decomposing the related metric for that FR. Given that all of Suh's textbook (1990, 2001) designs feature metrics, a corollary for using metrics while designing should certainly be considered.

A performance measurement system should evolve over time. A performance measurement system might prove valuable to a company by measuring a few top-level metrics but might lose value over time.

Alternately, an evolving performance-measurement system with metrics at each level can better avoid obsolescence with a plan to evolve to measure future metrics that have not yet been included in the current system. Having metrics at every level of the design hierarchy can facilitate identifying where future metrics might fit in the system and pinpoint any currently controlled functions that might affect those metrics.

1.3 State of the Art

1.3.1 Linking Financial and Performance Metrics

Using metrics to gauge the success of a process or solution has been used for the better part of a millennium. Financial metrics have been used since at least the Middle Ages to measure success. Financial metrics are defined as the key numbers focused on in a financial statement. Double-entry accounting had been used to resolve any disputes that would arise between traders and keep a record of what was owed. This began to evolve into cost accounting in Europe in the twelfth century, with the increased demand for textiles. The slow output of textiles increased the demand and therefore the cost. However, instead of having work more often, artisans actually worked less (Johnson 1983). A backward-bending supply labor curve explains this phenomenon, in which, after reaching a certain wage level, workers are able to make more money than their desired lifestyle demands. A worker will then choose to work less time to earn the same overall desired income and enjoy more leisure time (Hanoch 1965). As a result, merchants began hiring artisans to produce textiles for a negotiated steady wage. This wage contract was not sufficient to gauge the labor productivity, and so cost accounting was developed to assess labor productivity and reduce slack in the process (Johnson 1983). From that time until the 1980s financial metrics have been used as a measure of ROI and assumed effectiveness (Bruns 1998).

By 1925, most cost accounting theories had been developed and used, until the changes in the 1980s, when it became widely accepted that financial metrics alone were not enough. Kennerley and Neely (2002, 2003) wrote a useful history on management systems that has been used to find many of the sources to follow. Firms became more decentralized and were split into different departments. Owners and managers were no longer the same entity. Owners needed a metric to judge the effectiveness of the managers they employed. This metric was an important milestone called ”return on investment,” developed by DuPont in 1912. ROI was used to motivate and assess managers’ effectiveness and efficiency (Kaplan 1984).

There have been opponents to the practice of solely using financial metrics since the start of the nineteenth century. However, it was not until the competitive manufacturing environment of the 1980s, when a belief arose, asserting that top-level financial metrics alone were not sufficient for improving or controlling systems (Johnson and Kaplan 1987). At the beginning of the twentieth century, Frederick Taylor observed the failures within the steel industry, which came from measuring ROI alone. Workers would customarily practice what was termed ”soldiering,” which meant operating well below their potential performance level. This was attributed to three main causes. First, as the industry only measured ROI, workers were afraid that some jobs would be eliminated if ROI improved too much. Second, a wage system with no incentives for effectiveness led to atmosphere of doing just enough work to not be fired. Since there was no measure on effectiveness and no benefit for being more effective, workers were afraid to set a precedent of higher productivity that managers would then demand. Third, there were no standardized methods for doing work based on the level of effectiveness (Taylor 1914).

From the 1970s to the 1990s, the failures of calculating ROI as a measure of productivity are common within the literature. Focusing on traditional measures, like cost, can encourage “short termism,” which the *Financial Times* defines as an excessive focus on short-term results at the expense of long-term interests (Kennerley and Neely 2002). Dixon et al. (1990) wrote that financial metrics only provide a measure of past financial performance and are unreliable for predicting the future. The priority placed on financial metrics, which focus on short-term cost reduction and favorable quarterly statements is the cause of America’s decline in productivity and is a relevant factor for other countries. Managers are hesitant to take risks for fear of financial short-term loss. As a result, they shy away from innovation, a necessary step in developing more productive processes. (Hayes et al 1990, Richardson and Gordon 1980). Furthermore, systems that measure financial metrics alone cannot properly reflect a change to more effective processes.

Another problem with focusing on top-level financial metrics is that a system might appear to be functioning efficiently at the cost of functioning effectively (Austin 1996). The value of a company will seem to rise when resources are no longer applied to such processes as new product development, an improved production process, worker skill improvement, and customer awareness campaigns. Even though these are necessary investments that lead to long-term success, systems that measure financial metrics alone would view these cost reductions as improved ROI, which they are not (Kaplan 1986). Financial metrics can also overlook customers and competitors. Organizations achieve success by satisfying their customers’ needs and being more effective than their competitors. Effectiveness measures the extent to which the customer’s needs are met, while ROI is internally focused on how economically the organization's resources are used and provides no information on what the customer wants or what a competitor is doing (Neely 1995).

1.3.2 Performance Measurement Systems

Ineffective financial metric based performance systems led to the demand for performance systems that measure both effectiveness and ROI, many of which have been developed since the 1980s. This is in part due to the influence of effectiveness on ROI, based on the path dependency of effectiveness and ROI. One example of this is product reliability. Higher product reliability is part of an effective process and can lead to higher customer satisfaction. It also affects ROI by reducing the number of products that need to be produced and losses due to warranty claims (Neely 1995). There are three main performance measurement systems to consider that take different approaches to linking effectiveness with ROI: the Balanced Scorecard, the Strategic Measurement and Reporting Technique (SMART) pyramid, and the Performance Prism.

1.3.2.1 Balanced Scorecard

One of the most commonly used performance management system, the Balanced Scorecard, was developed by Kaplan and Norton (1992). Kaplan and Norton believe that companies suffer from one of two problems. First, some companies rely on traditional financial metrics that measure ROI but neglect to measure effectiveness and so do not prioritize continuous improvement and innovation. Second, some companies have too many metrics, since new metrics are added every time an employee or consultant makes an insightful recommendation. The Balanced Scorecard (BSC) provides a set of top-level metrics for large companies to measure success (Figure 1). The goal is to prioritize effectiveness and ROI while preventing information overload that results from too many metrics. Kaplan and Norton propose looking at a company from four perspectives:

(1) The financial perspective: how we look to shareholders
(2) The customer perspective: how customers see us
(3) The internal business perspective: what must we excel at
(4) The innovation and learning perspective: ways to continue to improve and create value

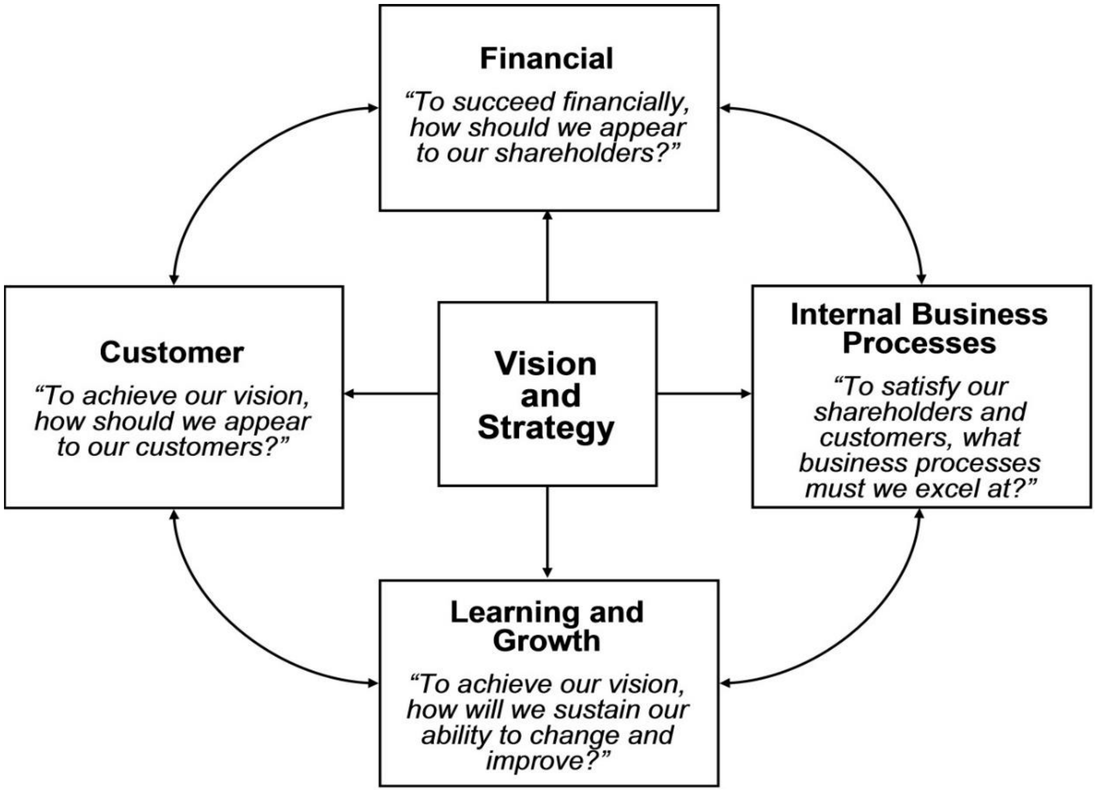


Figure 1: The Balanced Scorecard (Kaplan and Norton 1992)

One result of companies implementing the BSC is increased involvement from senior managers who have the most complete view of the company's goals and priorities. This is of interest because traditional financial metric systems are usually overseen by financial experts; rarely are senior managers involved.

There are some weaknesses to the BSC. The BSC does not provide a way to measure performance at the manufacturing level. Also there are weaknesses in measuring long-term goals and performance metrics that relate to employees, suppliers, and stakeholders (Susilwati 2013). Data gathered by the Balanced Scorecard Collaborative suggests that over fifty percent of businesses in the USA adopted the BSC by the end of 2000 (Kennerley and Neely 2003).

1.3.2.2 SMART Pyramid

The SMART pyramid (Figure 2) was designed at Wang Laboratories in Lowell, Massachusetts, as a performance metric system to link financial metrics with performance (Lynch and Cross 1991). A survey taken in the 1980s of 260 financial officers and 64 operation executives, by the National Association of Accountants, shows that before SMART, 60% of those who took the survey were unsatisfied with their performance measurement system. In the electronics industry, this number is closer to 80%. SMART addresses four major managerial complaints:

(1) Current performance measures provide irrelevant or misleading information that conflict with the achievement of strategic objectives.

(2) Metrics collected in isolation distort management's understanding of how effectively the organization as a whole is operating.

(3) Traditional measures do not consider satisfying customer requirements.

(4) Financial metrics like profitability come too late to allow for mid-course correction.

The SMART pyramid attempts to measure how departments function separately and together to

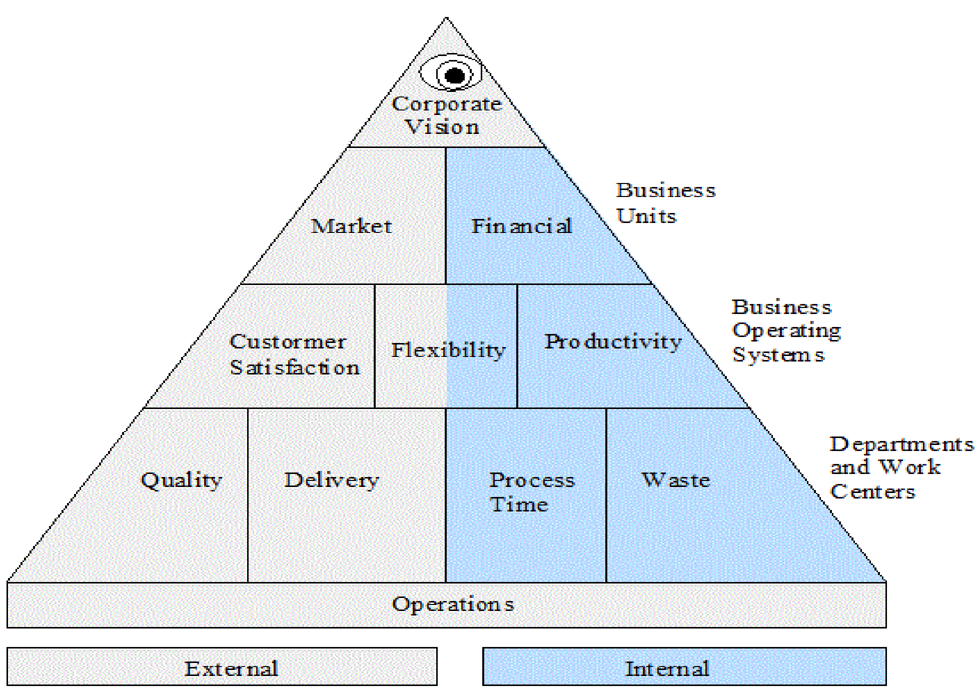


Figure 2: The SMART Pyramid (Lynch and Cross 1991)

achieve long-term goals. Financial and performance information is linked in a way that is useful to operations managers. Furthermore, all business activities are focused on requirements dictated by the customer. Lastly, SMART includes a framework for changing performance and incentive systems, as necessary. The result is a four-level pyramid that links effective operations with corporate-level ROI strategies. The top-level is the vision that serves as the basis for corporate strategy. At the second level, called "business units," relevant financial metrics are defined, e.g. positive cash flow, profitability, market penetration and strategies, which are to be measured and controlled. At the third level, a business operating system (BOS) is defined for each metric at the business unit level. A BOS contains three operational objectives: customer satisfaction, flexibility, and productivity relevant to the financial metric. By using a BOS to support individual financial metrics, departments are able to focus on their effectiveness rather than their ROI. The relation between the operational objectives and the financial tier above it is represented by the blocks in the tier below. For example, the "financial" block in the "business units" tier sits on top of "flexibility" and "productivity" in the lower tier, and likewise the financial measures depend on productivity and flexibility. The fourth level of the pyramid indicates the day-to-day metrics that need to be controlled to achieve all of the higher-level goals (Lynch and Cross 1991). A notable weakness of the SMART pyramid is that, while it links ROI and effectiveness, it excludes continuous improvement (Susilwati 2013).

1.3.2.3 Performance Prism

Kennerley and Neely (2000) take a different approach than the BSC and Smart Pyramid with their Performance Prism. They believe that it is a misstep for metrics to be derived from a strategy, arguing that metrics are derived from the wants and needs of the various groups of stakeholders. The Performance Prism looks at five perspectives to add value to stakeholders by assuring that their wants and needs are satisfied. The first perspective is stakeholder satisfaction. An organization must determine the most influential group of stakeholders and its wants and needs. The second perspective is the strategies to satisfy customer wants and needs. Metrics serve four functions within the strategy perspective:

(1) Track whether or not the necessary strategies are being implemented
(2) Communicate the strategies within the organization
(3) Encourage and incentivize implementation of the strategies
(4) Determine how successfully the strategy is working

The third and fourth perspectives focus on performance, the processes required to be able to execute the determined strategies and what capabilities are needed to operate those processes. The fifth perspective is stakeholder contribution, as opposed to stakeholder satisfaction in the first perspective. This perspective is considered important because customer satisfaction is often not an accurate measurement. In the early 1980s, a company might measure customer satisfaction by the number of customer complaints received. This might be a misleading metric, if only some unsatisfied customers make the effort to complain. Given that stakeholders want and need something from the organization, the reverse is also true, and the two are not the same. In the case of customers as stakeholders, they want a product that provides value at an acceptable price. The organization wants a loyal and profitable customer base, which are the stakeholder contributions, loyalty and profitability. Figure 3 shows the different stakeholder wants, needs, and contributions. Kennerley and Neely (2000) write that often this is where most performance measurement systems stop, once they have been implemented. However, to ensure the effectiveness of the measurement system, the organization must regularly refresh and refine the measurement system to

Figure 3: The Performance Prism (Kennerley and Neely 2000)

make sure the metrics stay relevant within the current stakeholder wants and needs.

1.3.3 Evolving Performance Measurement Systems

1.3.3.1 Reasons for Evolution of a Performance Measurement System

A common problem in many performance measurement systems is the lack of evolution over time, as the needs of the organization shift. Evolution is defined as a regular review and adjustment of the performance system and the metrics within to ensure that the system remains useful to an organization. Between 1995 and 2000, about half of all organizations in the US have developed new measurement systems (Frigo et al. 1999). However, almost all of these new measurement systems are static in nature. A review of academic literature in the fields of psychology, organizational behavior, and management accounting shows four categories that serve as sources for evolution (Waggoner et al. 1999).:

(1) Internal forces, e.g. dominant coalition interests
(2) External influences, e.g. market volatility
(3) Process issues, e.g. manner of implementation
(4) Transformational issues, e.g. risk of gain or loss from change

1.3.3.1.1 Main Obstacles Inhibiting Evolution

There are four main reasons why evolution of a performance system can be inhibited (Grenier 1996):

(1) Institutional obstacles
(2) Pragmatic obstacles
(3) Technical obstacles
(4) Financial obstacles

The first cause is institutional obstacles. The background of many of today's managers has been one of using instinct versus performance data to make decisions. Many decisions come from political pressure within an organization and agreed-upon strategies to keep power in the hands of certain individuals, making performance data a moot point. There is also a reluctance to use performance data because of the clarity it provides about both good and bad performance. Many managers prefer to report information in a way that illuminates their success and are hesitant to welcome the increased accountability that comes with increased performance measurement data.

The second cause that inhibits evolution is pragmatic obstacles. Often, to prove legitimacy, the performance measurement system becomes an imitation of a system that had shown success in a similar organization (Waggoner et al. 1999). Without proof of the success of a process in a previous instance, an organization is hesitant to try it. As happened with the Toyota Production System (TPS), once another organization sees the success of a system, it wants to create its own version. Another pragmatic obstacle is that many managers claim that their metrics tell them what they already know to be true. In addition, performance data is sometimes blamed for a bad experience that is really caused by human factors, such as the time and frustration that goes into agreeing on what metrics should be measured. Also, managers will claim to have little faith in performance data due to the increased amount of attention it will require from them. It is easier to make a decision across the entire board than by individual departments, based on performance data.

The third major reason inhibiting evolution is technical obstacles. There can be confusion about what constitutes performance, or there may be difficulty in making the performance data available in a timely fashion to assist with routine decision making. Also, what can be perceived as a large number of performance metrics can lead to information overload.

The fourth reason is financial obstacles. This is somewhat more obvious and relates to budgetary issues (Grenier 1996). As a report from the U.S. General Accounting Office (1993) states, "The success of a program is not important if we can't afford it."

After a multi-layer case study of barriers to evolution in seven organizations, four categories of obstacles to evolution are evident:

(1) Process: Lack of an effective way to reflect on their performance management system, and two organizations note that there is not any managerial time set aside for reflecting on the performance measurement system

(2) People: Lack of personnel with the skill to analyze collected data and identify necessary performance measures. One company notes that the rate of staff turnover makes it difficult to identify and manage necessary performance measures
(3) Infrastructure: Inflexible legacy systems, specifically enterprise resource planning, are noted as a barrier that makes data collection and reporting a challenge, as are other "off the shelf" inappropriate systems implemented by upper management
(4) Culture: Individuals in different organizations are resistant to reflecting on and modifying the performance measurement system, because it highlights areas under their responsibility.

Another noted cultural barrier is the lack of alignment of performance measures with rewards, which can provide incentive to evolve the system (Kennerley and Neely 2002).

1.3.3.1.2 Other Obstacles to Evolution

There are a few other obstacles to evolution noted by a variety of authors. One is the political landscape of organizations, in which different constituencies vie to promote measures that serve their interests. These interests might or might not be linked and can sometimes negatively affect each other. As a result, the performance measures that are prioritized tend to reflect the interests of the dominant constituency (Hirsch 1995). When one constituency is not dominant, the result is often a compromise, in which the resulting metrics represent a negotiation between the different constituencies. Bitici (2000) writes of three obstacles to evolution within a performance measurement system:

(1) A lack of a structured framework that allows organizations to differentiate between improvement measures and control measures, and thereby develop causal relationship between competitive and strategic objectives and processes
(2) Absence of a flexible platform to allow organizations to effectively and efficiently manage evolution within their performance measurement system
(3) Inability to identify the relationships between measures within the system

Evolution is a significant part of a performance measurement system's long-term health. To avoid obsolescence, a performance measurement system must evolve over time to remain relevant as the needs of the organization shift. This improves long-term profitability by being more effective over time and saving an organization the expense of having to develop a new performance measurement system (Kennerley and Neely 2002).

1.3.1.1.3 Performance Paradox Model

The performance paradox model (Meyer and Gupta 1994) explains the inevitable need for evolution as a requirement in every performance measurement system. When performance is measured, there must be some sort of appraisal or review to determine how successful the organization currently is. Appraisals are beneficial for an organization, since they highlight ways for the organization to improve. Over time however, these appraisals lead to the decline in effectiveness of the existing prioritized metrics. An organization will alter its performance in order to improve the prioritized metric, and so the metric becomes a measure of how well an organization can prioritize the metrics versus how well the organization is performing overall. This erosion of the current metrics is called the running-down process, which is made up of four key factors:

(1) Positive learning
(2) Perverse learning
(3) Selection
(4) Suppression

Positive learning is defined as the improvement of an organization over time with respect to a certain prioritized metric due to awareness of that metric. When the metric is first introduced, the improvement might be drastic, but as an organization begins to reach maximum capabilities, the variability in that metric over time decreases.

Perverse learning is the reduction in an organization’s overall performance due the workers’ focus on improving the prioritized metrics rather than their performance as a whole. Similar to what occurs with positive learning, the variability of the prioritized metrics will be reduced as the organization nears its maximum capabilities, but these metrics represent only an artificial measure of the organization’s performance.

Selection is defined as a reduction in the variability of a performance metric over time, due to a higher starting point with respect to prioritized metrics. Any new process or employee brought into the organization will have a higher starting point with respect to that metric. As a result, variability will be reduced.

Suppression is related to perverse learning and is the inaccurate measuring or reporting of metrics that shows reduced variability and misleads observers. An example of this was in the British National Health Care Service. The metric being measured was wait time for an operation, which was to be no longer than two years. Average waiting time decreased according to the metric, but only as the result of suppression. Waiting time was measured from the first hospital consult to the time of the operation, and so the first hospital consult was being regularly postponed to influence the metric. Waiting time appeared to decrease, when, in fact, it had not (Smith 1995).

The solution is to define a new set of performance metrics that measure the same properties as the previous ones when variability becomes stagnant (Meyer and Gupta 1994).

1.3.3.2 Approaches for Evolving Performance Measurement Systems

There are several approaches to creating an evolving performance-measurement system. One of these is the reengineering over regular intervals (Hammer 1990). Reengineering is defined as using the power of modern information technology to radically redesign a business process in order to achieve dramatic performance improvements. Modern information technology does not necessarily deliver impressive results due to its primary use in automating processes previously done by humans, in order to improve ROI or speed up an old process. Certain departments or lower-level processes within a system will be overhauled to improve the system, but by overlaying improvements onto the existing system, the potential benefit is reduced. An organization must constantly question every step in a process as well as the value it is adding to the customer or stakeholder. There must be openness to changing any aspect of the organization, as a change to one part of the organization might require changes in other parts. Hammer (1990) argues that the goal of evolving should not be to automate and make a process more efficient but to create dramatic improvements to effectiveness through the design of a new process.

Reevaluation of the effectiveness of the current functional metrics at regular intervals seems to be a staple in any evolving performance-measurement system. A nine-step flow diagram for developing an effective performance-measurement system by Wisner et al. (1991) features "periodically re-evaluate the appropriateness of the established performance measurement system in view of the current competitive environment." Bitici (2000) writes that for an evolving performance measurement system to be effective, it should have four parts:

(1) An external monitoring system, which continuously monitors developments and changes in the external environment
(2) An internal monitoring system, which continuously monitors developments and changes in the internal environment and raises warning and action signals when certain performance limits and thresholds are reached
(3) A review system, which uses the information provided by the internal and external monitors and the objectives and priorities set by higher level systems, to decide internal objectives and priorities
(4) An internal deployment system to execute the revised objectives and priorities to critical parts of the system

A case study by Kennerley and Neely (2002) determined four needs for the effective management of an evolving performance measurement system:

(1) Active use of the performance measurement system
(2) A performance measurement system consisting of three interrelated elements: individual measures, the set of measures, and the infrastructure that enables data acquisition
(3) Four stages of evolution: use, reflect, modify and deploy
(4) Elimination of barriers that prevent evolution, which can be classed into four main categories to be considered during the four stages of the continuous improvement: process, people, infrastructure, and culture

In this case, the interval for reevaluation is not regular with respect to time but instead triggered by different stimuli. If the system is actively used, any one of these stimuli can begin the evolution cycle. These stimuli can be external, for example, a change in the market or internal, established management meetings. Another common example worth noting that could regularly lead to the need for reevaluation is a change in customer needs. Once reevaluation is triggered, every part of the current performance system is critically reviewed to determine its relevance with respect to the stimuli. This enables necessary changes to be identified, which triggers the next step, system modification. Once the system has been modified, it is deployed and goes back into regular use.

1.3.3.3 Determining Actionable Metrics

During the initial design and evolution of a performance measurement system, it is important to have a method for determining whether a proposed metric is actionable. Literature on designing metrics offers a list of criteria for potential actionable metrics that can be compiled (Neely et al 1997):

Performance measurement record sheet
Title
Purpose
Relates to
Target
Formula
Frequency
Who measures?
Source of data
Who acts on the data?
What do they do?
Notes and comments

Figure 4: Performance measurement record sheet (Neely 1997)

- derived from strategy
- simple to understand
- able to provide timely and accurate feedback

- based on quantities that can be controlled by a user
- able to be related to specific goals
- relevant
- focused on improvement,
- based on an explicitly defined formula and objective

The performance-measurement record sheet (Neely 1997) addresses many of these criteria, with a list of criteria that must be present for a metric before it can be considered actionable (Figure 4). A good title should indicate the metric and should be devoid of jargon. Without purpose, it is moot whether or not a metric is actionable. The rationale for the metric should also be specified, for example, "to reduce costs due to lead time." An actionable metric must be tied to the top-level metric. Target levels for each metric specify the required level of performance for the system to remain in good standing, whether that is specified by management, the customer, or in comparison to a competitor. The formula is the equation used to connect that metric to those at higher-levels and lower-levels. An example of this could be the time to offer a quote to a customer, which might be the time the customer received the quote minus the time the quote was initially requested. The definition of this formula is important because it should reflect only that which can be controlled and can induce good business practices. The frequency is how often the metric should be measured and is a function of the importance of that metric and the volume of available data. Identifying who measures a specific metric ensures that someone is responsible for consistent collection of that metric and provides traceability. The importance of the source of the data lies in the fact that a consistent source is required if performance is to be measured over time. Knowing who acts on the data ensures that someone is responsible for controlling and improving that metric. "What do they do" is perhaps the most important part of this sheet. It ensures that the management loop is closed and defines the management process to be followed whether the metric depending on whether the value of the metric is acceptable or underperforming. An example of this could be "appoint a team for determining why lead time is above X amount of time."

Another method for determining whether or not a metric is actionable was developed using a series of tests compiled from literature on the topic (Kennerley and Neely 2003). If the metric fails any of the tests in Figure 4, it cannot be considered actionable without some modification.

The effectiveness of a metric is related to its ability to be controlled by a user. "One of the golden rules of performance measurement is that there is no point measuring someone on something over which they have no control" (Neely 1997).

1.3.4 Control Systems

An organization with or without a performance measurement system is parallel to modern control theory of closed or open loop systems. Control is defined as obtaining a desired system response (output) based on a specific stimulus (input) (Dorf and Bishop 2001). “Control theory provides a systematic approach to designing closed-loop systems that are stable in that they avoid wild oscillations, are accurate in that they achieve the desired outputs, and settle quickly to steady state values (Abdelzaher 2008).” The simplest form of a control system is an open loop system. An input is put into a system and an output is generated with no feedback provided. A simple example of this would be a sprinkler system watering grass. An input of a length of time is put into the system, and the system runs for that length of time. There is no feedback on how wet the grass became, nor does the sprinkler operate until it achieves that desired level of wetness. This is the same for a system without metrics (Figure 5). The user cannot quantitatively assess the difference between the desired and actual output or modify the DP to achieve the desired output.

In a closed-loop system, a sensor sends feedback into the system, which measures the error. Error in this situation is defined as the difference between the desired output and the actual input. As long as the error is above zero or outside of some defined tolerance, the error tells the controller to take some action until the error is within tolerance (Owen 2012). This is no different from a performance measurement system in which the user modifies a DP to get the desired output (Figure 6). Once the value of the actual performance is within the tolerance of the desired performance, the modification can stop.

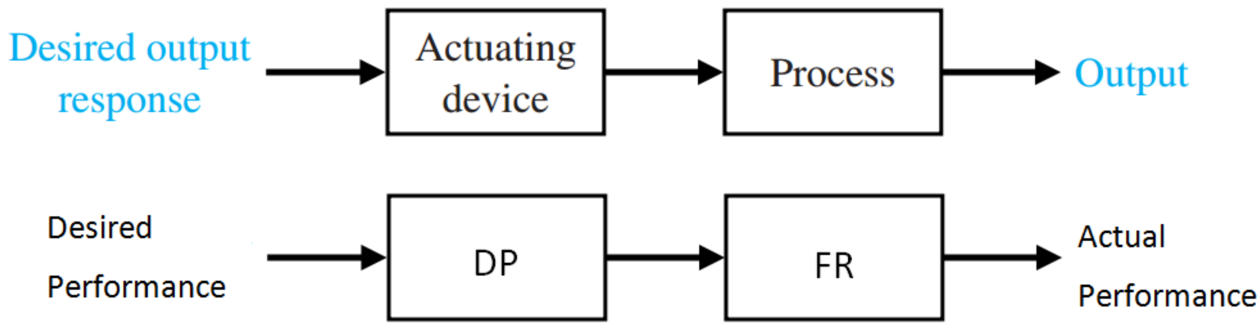


Figure 5: Open-looped control system

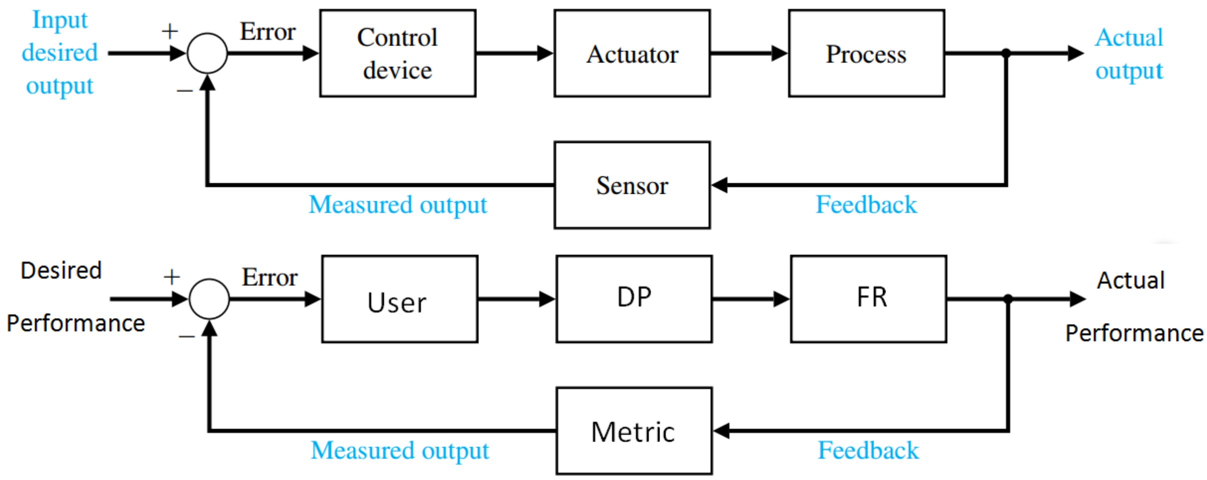


Figure 6: Closed-loop control system

One possible issue is disturbances that can occur to the system and which require non-value added corrections to be made. In some cases, this might be out of the user's control. For example, in trying to set a speed in driving a car, the user might modify the force upon the gas pedal to achieve a desired speed. However, the presence of a hill or valley might create a disturbance requiring undesired modifications to the force on the pedal to achieve that speed. In other instances, disturbance might be due to coupling within a larger system, requiring non value added iterations to get back within tolerance. In axiomatic design, similar closed-loop systems (Figure 7) are illustrated by Suh (1998) to show different levels of coupling. Coupling occurs "when a FR cannot be easily controlled, in that it requires iteration to arrive at its fulfillment" (Brown 2006). More broadly, Craig Borysowich (2007) defines coupling as "the measure of dependency between two modules. Coupling measures the likelihood of a change or fault in one module affecting another module."

Figure 7 illustrates the three levels of coupling. Each node represents a FR DP pair (Suh 1998). The first control system represents an uncoupled system. Both of the children FR DP pairs are independent and therefore can be satisfied in any order without causing unintended consequences on each other. The satisfaction of the parent FR DP pair is a combination of the satisfaction of the children and that combination is represented by the "S" junction. The second control system with the "C" junction represents a decoupled system, also often called a partially coupled system. In this setup, the left FR DP pair has an effect on pair on the right and so an order of operations must be performed to satisfy both pairs in one iteration. The left pair must be controlled first so that the right can be controlled to correct the unintended consequence that the left pair had on it and achieve the desired result in a single iteration. Left and right refer to the tendency to reorganize decomposition from left to right when an order of operations exists in a decoupled system. The third system, with the "F" junction, represents a fully coupled system. A change in either FR DP pair has an effect on the other and so the output of both must be fed back into the system to converge on the desired output over multiple iterations. There is no guarantee that a coupled system will be able to converge upon a solution. This can quickly become an uncontrollable system (Suh 1998).

1.3.5 Axiomatic Design

AD's principles provide a methodology for controlling a design solution and features two axioms, which are the rules that all good designs adhere to in order to maximize the probability of successfully satisfying the customer need. Axiom one states that a good design maintains independence of the FRs

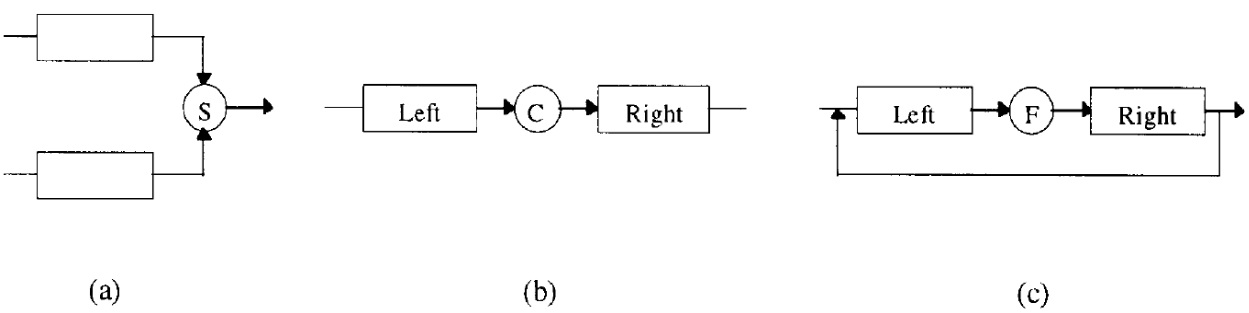


Figure 7: Coupling control systems (Suh 1998)

within. Axiom two states that minimizing the information content of the design improves the probability of designing a successful solution (Suh 1990). Axiom one relates to the level of control within a system. Control can be challenging to achieve when inputs in other parts of the system has an unintended effect on a certain output. To prevent this from happening, each FR in a system should have a DP that affects only the FR it is paired with, improving control of the system (Suh 1990).

AD encourages CEME, which can be beneficial to designing a controllable system. Originally, this was known as MECE, "mutually exclusive, collectively exhaustive," a method for reducing the parts of a system to non-overlapping modules to make sure no part of the system has been unaccounted for (Rasiel 1999). This was changed to CEME, with the belief that the first step is to make sure everything has been thought of and then ensure independence of the elements to ensure control.

1.3.5.1 Suh's Return on Investment Decomposition

At the inception of AD, Suh's (1990) illustrated designs featured metrics. One of the more famous of his designs, and certainly one of the most referenced when explaining the basics of the two axioms, is the water faucet design. Faucets have historically featured hot and cold water handles. Faucets have two functions:

FR1: control flow

FR2: control temperature

The problem with the two-handle design is the coupling due to each of the handles. Both left and right handles are the DPs for controlling flow and controlling temperature, and so controlling one of the functions affects the other. Suh discusses a different type of handle to control flow and temperature independently. To control FR 1, which is flow, Suh assigned the metric (Q). DP 1 is the height that the handle is raised, which is measured by the metric (Y). FR 2, temperature, measured by the metric (T), is controlled by the angle the handle is rotated in either direction, and is measured by the metric (Phi) (Suh 1990). The metrics neither combine to equal a top-level metrics nor are used to define children FRs, but they show intent to use quantitative metrics to measure the output of the controlled system.

Metrics have previously been used in axiomatic design to decompose a CEME design solution. An example of this can be seen in Suh's second book (2001). Suh's (2001) decomposition of ROI is the basis of this doctoral work (Figure 8). The equation used by Suh is:

ROI = ((Sales revenue – Cost) / Investment)

While he might not necessarily use the word metric, this equation is used to measure how successfully FR 1, maximize return on investment, is satisfying the related customer need. The difference between this design and the faucet design is that this metric, ROI, is dependent on other variables that combine to equal ROI. Another difference that shows the value of metrics is that the next level of FR DP pairs is used to control each of the variables in the equation independently. This continues another level lower in the decomposition, with the equation:

$$\text{Revenue} = (\text{Price x Volume})$$

This equation is the metric for FR 1. The children of FR 1 are designed to control each variable in that equation:

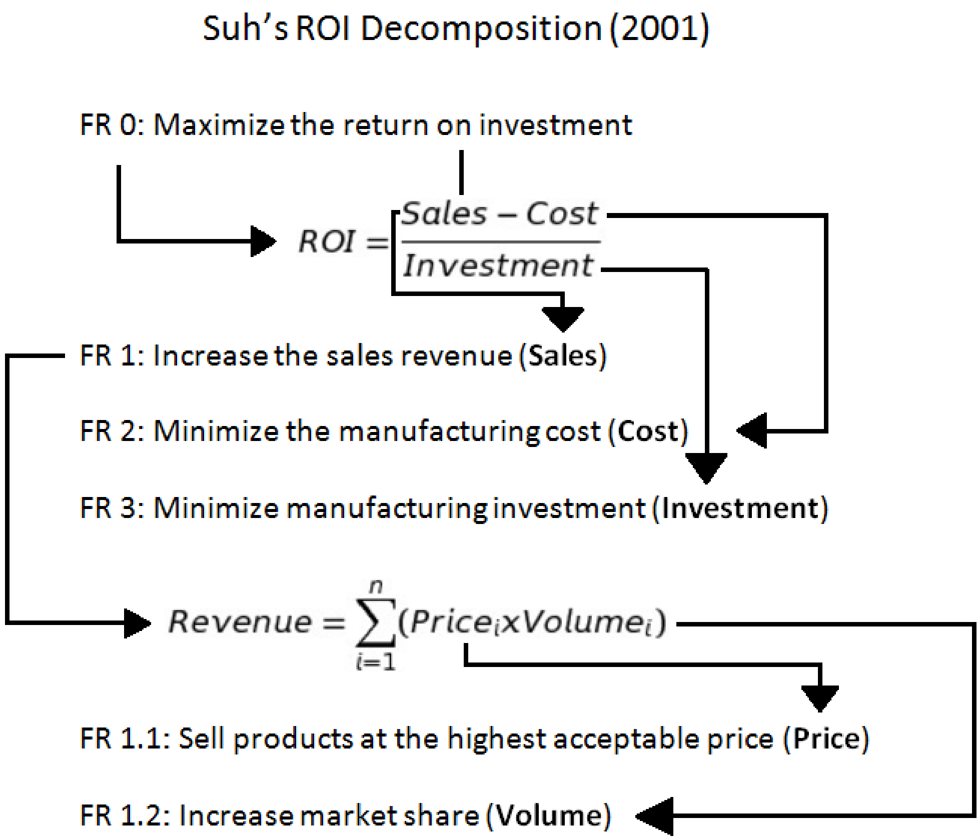


Figure 8: Suh's ROI decomposition (Suh 2001)

FR 1.1: Sell products at the highest acceptable price (price)

FR 1.2: Increase market share (volume)

This zig zag decomposition using metrics can facilitate decomposing and determining CEME at each level. This shows a similarity in philosophy shared by some authors, who agree that a successful design that provides control should have metrics attached to every function in the system (Melnyk 2002, Brown and Dickinson 2009).

1.3.5.2 Manufacturing System Design Decomposition

Axiomatic design uses metrics to design templates for manufacturing companies to increase control of their ROI. Manufacturing system design decomposition (MSDD) decomposes ROI using metrics at the top-levels (Cochran 2002). MSDD was designed as a possible solution to the problem of satisfying top-level goals without clear definition of sub-processes to accomplish these goals. Based on Suh's (2001) ROI decomposition at the first two levels, this design takes a different approach lower in the decomposition process (Figure 9). Cochran considers his decomposition decoupled versus uncoupled, and so there is a necessary order of operations. DP 1 "production to maximize customer satisfaction" must be adjusted to "maximize revenue," first, since the DP for doing so will affect FR 2 and FR 3: "minimize cost" and "minimize investment." ROI can technically be increased by reducing cost but can become a detriment without the consideration of how it will affect adding value to the customer. Like Suh, Cochran does not specifically mention decomposing by metrics in this design, but it is obvious that the first two levels of FR DP pairs are to control the variables in the ROI equation. The children of "maximize

Cochran's MSDD (2002)

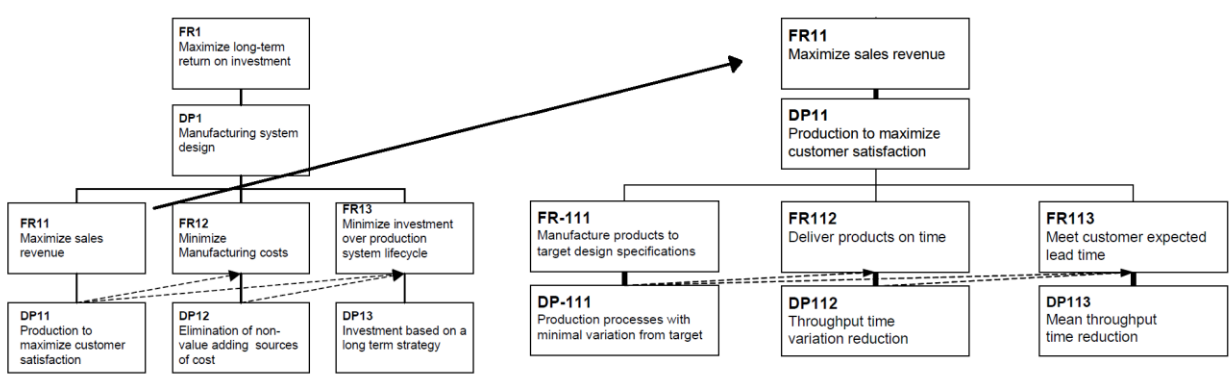


Figure 9: Cochran's MSDD: The top two levels (Cochran 2002)

revenue" in Cochran's decomposition differ from Suh's. Cochran's decomposition does not feature a specific equation for the revenue metric, but he does explain that controlling revenue is a combination of controlling "meeting customer specifications," "delivering products on time" and "reducing lead time." At the lower-levels, this concept is not as obvious, and no equations are mentioned for determining which variables to control. Cochran's later work starts to incorporate metrics at each level.

1.3.5.3 Collective System Design

Cochran created collective system design (CSD), which features metrics on both the FRs and DPs (Cochran 2013). CSD (Figure 10) is a methodology based on axiomatic design theory for enterprise engineering, which is a sub-discipline of systems engineering. Value stream design language is used to articulate CNs into FRs. Each value stream designed is meant to be robust and controllable. This system provides a behavior and process for collective agreement during a company's conversion to lean, to

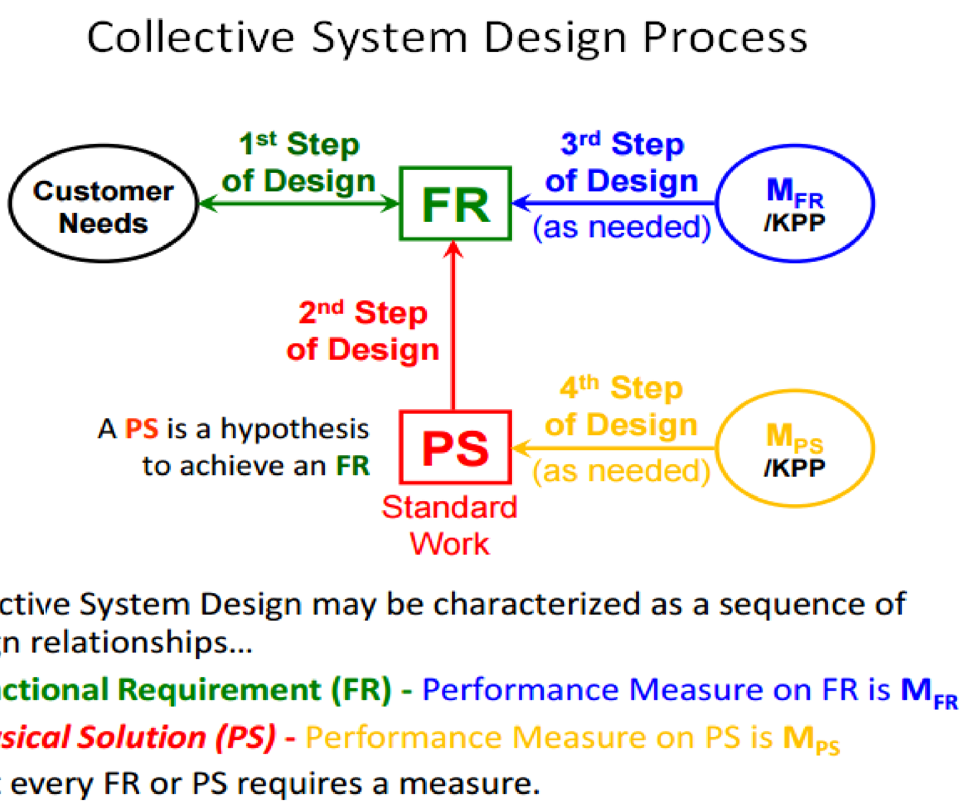


Figure 10: Cochran's Collective System Design (Cochran 2013)

achieve long-term sustainability. Management, engineering, finance, and other groups can have very different viewpoints of on how to satisfy CNs. CSD offers a framework to develop a shared intellectual model. DPs are known as physical solutions (PS) in this system but are DPs in every way. Each PS is a possible hypothesis for satisfying an expressed FR and must be agreed upon by all who work with the design. This method is similar to axiomatic design in translating customer needs into FRs and developing PSs to manage these FRs. CSD then implements metrics on both FRs and PSs. Metrics on FRs track how effectively the organization is achieving its FRs. Metrics on the PSs measure how effective the organization is at implementing the PS. Metrics for PSs can be binary, meaning either a 0, which would represent the PS has not been successfully implemented, or a 1 if it has been (Cochran 2013). CSD notes that metrics are only used as needed and not required at every level on the design. Each PS is implemented to specify the content, timing and sequence of the work, also known as standard work. In the event that the respective metrics are at an unacceptable level, there are three options:

(1) Improve the standard work without changing the PS
(2) Determine a new PS
(3) Change the respective FR

Cochran explains this with a traffic safety example, with the FR "safely regulate traffic." If the PS is not proving effective, three possible changes can be made:

(1) Change the timing on the light, which is the standard work
(2) Replace the light with stop signs, which is changing the PS
(3) Change the FR to "prevent road intersections," which would then have its own PS

This design uses metrics but does not use them or related equations to determine the next level of FRs.

1.3.5.4 Using Functional Metrics to Design CEME Solutions

Recently, there has been a return to using metrics to decompose design solutions in axiomatic design. A top-level FM is determined with a defined equation or mathematical expression that represents that metric and shows its connection to lower level metrics. A lower-level of FMs is designed, each of which is intended to independently control one of the variables in the equation or expression above. This process is repeated until the metric is no longer the result of combining any smaller variables or the method for determining that variable is obvious. FR DP pairs are created once the FMs have been fully decomposed to control each related metric. This method provides quantifiable justification for CEME (Henley 2015).

1.3.6 Metrics in Sports

In professional sports, lower-level performance metrics are starting to be linked to traditionally measured top-level metrics to improve the level of success of the top-level function**.** Lewis (2004) writes about the failure within professional baseball to identify the appropriate metrics. For decades, teams bought players in an attempt to increase wins using statistics, which were believed to have the highest correlation with winning. Stats such as batting average and runs batted in (RBI) have historically been used. Statistical analysis shows that on base percentage (OBP) has a higher correlation with runs scored, which is a requirement for winning. With this information, the 2002 Oakland Athletics team was able to win the most games of any team in the league during the regular season, despite paying the third-lowest salary to its roster. The team also held the American League record at one point for most games won in a row, at 20 wins.

1.3.6.1 Expected Point Value

There has been statistical analysis done on decision-making in football, based on the expected point value (EPV) gain or loss in each situation. A common thread is that decision-makers for the team during a game tend to be risk-averse, to the point of reducing their chance to win (Carter, 1970, Urschel 2011).

A study was performed to analyze the importance of starting field position (Carter et al 1970). Studying over 8,300 plays over the first half of the 1969 professional football season, analysis was done to determine the value of each starting position with first down and ten yards to go. With 99 yards on the field, which translate to 99 starting points and 4 possible scoring possibilities on each play, (+7 for a touchdown, +3 for a field goal, -2 for a safety and -7 for a defensive touchdown against), there are 103 possible outcomes. However, this system with 99 equations and 99 unknowns was without enough data to predict the 99 probabilities accurately. Dividing the field into ten-yard strips, 90 – 81 yards to go for example, more accurate probabilities could be determined (Figure 11). In this table, each ten-yard strip is labeled by its midpoint; 90-81 is labeled as 85 for example. It is worth noting that the scoring value is essentially zero starting at the opponent's 20-yard line, which is where most drives start, showing clever intuition from the rule-makers. It is also worth noting that at the time of this study, the rules were different in one important situation. Whereas now a turnover on downs happens at current field possession, in 1970 an incomplete pass on fourth down gave the ball to the opposite team on the 20-yard line, if the current line of scrimmage was between the opponent's 20-yard line and the goal line.

An interesting point arises relevant to decision-making within the 5-yard line (Carter et al 1970). Commonly, on fourth down, a team will choose to kick a field goal for 3 points, which succeeds roughly 75% of the time, and usually gives the ball to the opposite team on or near the 20-yard line. This position is considered to have roughly an expected point value of 0 from the earlier table (Figure 11). The other choice is to go for a touchdown, which will give 7 points roughly 25% of the time, which, if successful, will also start the opponent at the 20-yard line for possession. If the touchdown attempt fails, the opponent will have the ball within the 5-yard line to start, which has an expected point value of -1.2. The field-goal option (FGO), which is the choice of most teams, has:

$$\text{FGO} = ((.75 * 7) - 0) = 2.25 \text{ net value}$$

The touchdown option (TDO), has:

$$\text{TDO} = ((.25 * 7) - (-1.2)) = 2.95 \text{ net value}$$

Center of the ten-yard strip (yards from the target goal line): X	Expected point value: $E(X)$
95	−1.245
85	−0.637
75	+0.236
65	0.923
55	1.538
45	2.392
35	3.167
25	3.681
15	4.572
5	6.041

Figure 11: The expected point values of possession of the football with first down and ten yards to go for various ten yard strips (Carter et al. 1970)

Perhaps the non-traditional option here might yield more points scored over time. The exception to this is one of two situations:

(1) The game is ending and 3 points will tie or win the game for the team that currently has possession
(2) 3 points would result in two-score lead at the end of the game, all but ensuring a win for the team that currently has possession

1.3.6.2 Fourth Down Decision Making

There has been much analysis done specifically on the decision of going for it on fourth down or kicking the ball (Romer 2006). Similar to the previous argument, the net value comparison between kicking and going for it is the basis for the decision. In this situation, kicking refers to both punting and

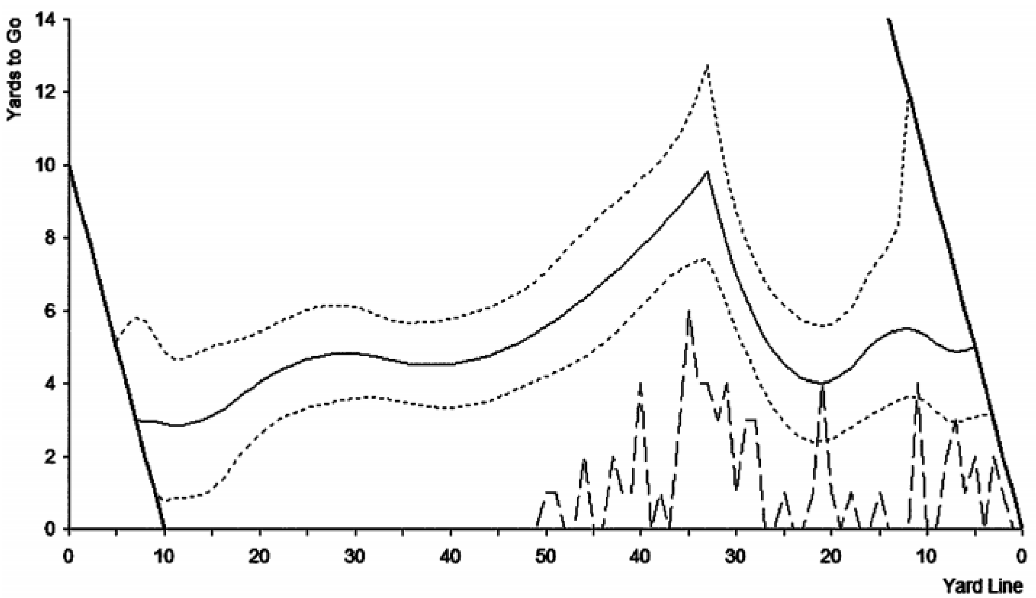


Figure 12: Break even line for kicking and going for it on 4th down (Romer 2006)

attempting a field goal. Unfortunately, due to the risk-averse nature of decision makers at this point in the game, there is limited data on the value of going for it on fourth down. Also due to the number of possible plays used, there are many different ways to go for the first down, so the data estimates must be smoothed. The decision is affected by both yards to go and position on the field. In general, the EPV on a possession goes up one point every 18 yards. A plot was generated that shows the break-even point for net EPV between kicking and going for it (Figure 12). If the situation is above the curve, the team's best option is to kick the ball. If the situation lies under the curve, the team should go for it. The dotted lines represent two standard error bands from the break-even line. The dashed lines on the bottom show the maximum yards to go in each situation, higher than which a team should kick the ball. The curve takes a significant dip at about the opponent's 30-yard line. This is because prior to that, punting will reduce the EPV of the opponent, thus increasing the net EPV. At the opponent's 30 yard line, the field goal becomes a reliable option for 3 points, creating a bigger jump in net EPV rather than just increasing it by reducing the opponent's EPV. To date, however, even with one yard to go on fourth down, teams will usually kick the ball, even at the loss of net EPV from that choice. It should be noted that this study does not take into account the strategic choices that might be made at the end of both halves of play, which are time-constrained situations.

The quantitative value increase of making decisions to maximize overall points has been analyzed, along with reasons why the gain must be substantial to ever be considered by a professional team (Romer 2002). Changing strategies in professional football is a risky proposition. Few teams use metrics or quantitative analysis for explaining decisions, which vary from the traditional intuitive mindset, can be difficult. There can be a fear in the coach's mind, the primary decision-maker, that taking a gamble can result in a loss. Even though it maximizes the point potential, losing a game based on a risky choice can cost him his job if he fails to get a win. This is a conflict of different top-level metrics being measured within the team. The coach is trying to control winning a game as well as maintaining employment. The owner is balancing winning games, as well as keeping the fans happy and the shareholders satisfied. However, over time the team is missing out on significant value. Third-down decisions in the first quarter of games are used to simulate fourth-down decision-making, since the behavior can be rather similar. A sample size of 992 cases over 732 first quarters was gathered, using situations in which the estimated value difference between going for it and kicking the ball was positive. This results in an average of 0.68 cases per team-quarter. On average, the expected gain from going for it was 0.37 points. And so, the expected benefit of going for it is 0.25 points per game. One point raises the chance of winning by 2.3% (Romer 2002), and so going for it in the first quarter in these situations can increase the chance of winning by 0.6%. Evidence based on third-quarter fourth down decision making suggests that the effect on winning would be even greater after the first quarter. The implications of applying better strategy based on this data can be substantial. Fourth downs only account for one thirtieth of all plays in the first quarter. Assuming a strategy to maximize points used in every quarter on fourth down, with an average of 8 fourth downs per game, the chance of winning would go up 4.7% (Romer 2002). This would allow a team to win one more game in three seasons out of four.

1.4 Approach

The solutions designed in this work attempt to improve on performance measurement systems that only prioritize ROI. This is in line with the thinking of Johnson and Kaplan (1987), Bruns (1998), and Dixon et al. (1990), who write that financial metrics are only a measure of past performance and are unreliable for predicting the future. Each of the design solutions in this work is intended to provide control of the top-level FMs to the user, by providing control of lower-level performance metrics that combine to equal the top-level metrics.

Similar to Kennerley and Neely (2002, 2003), Dixon et al. (1990), and Neely (1995), this work studies how to design solutions that measure and prioritize effectiveness. It is important that the system is as efficient as possible, but not at the cost of value to the customer due to decreased effectiveness. The top-level FMs are linked to FMs at each lower-level also, because relying on financial metrics alone can give an inaccurate measurement of the design solution's long-term health. This is similar to Goldratt (1983), who writes that focusing on financial metrics can make an organization inaccurately seem healthy. An organization's ROI might seem to improve as they ignore processes that have a negative effect on short-term ROI but are necessary for maintaining long-term ROI. This is also similar to Austin (1996), who writes that linking top-level metrics to lower-level performance metrics can facilitate tracing the root cause of underperformance in the system, which can go undetected even as it occurs.

This work features design solutions that can be considered evolving, in two forms. The first is a focus on innovation of the products and processes that make up the DPs, which provide the effectiveness within the design solution. This is similar to Hayes et al. (1990) and Richardson and Gordon (1980), who write about avoiding the habit of focusing on quarterly statements and neglecting processes like innovation that are necessary for long-term competitiveness. The second form is the regular review and evolution of the performance-measurement system to assure its continued relevance. This is similar to Kennerley and Neely (2002) and Meyer and Gupta (1994), who write that, over time, there will be diminishing returns on an organization's improvement. As the organization focuses on prioritizing certain metrics, it will get closer to its maximum capabilities and variability in the metrics will be reduced.

The method for determining whether a proposed FM is actionable is similar to Kennerley and Neely's (2003) performance-measurement record sheet and Neely (1997). As in Neely (1997), each FM is derived from strategy, easy to understand, focused on improvement, based on an explicitly defined formula, and controllable by the user.

The FMs in this work are similar to the measured values in control theory. The solutions designed in this work are similar to Dorf and Robinson's (2001) control-system theory. The systems are decomposed using FMs at every level to control the inputs at the lower performance levels. This is intended to generate the desired outputs in the top-level financial metrics. Similar to Abdelzaher (2008) and Owen (2012), the FMs provide measurements that the user can evaluate to determine the direction that the system must go in, so that the error term between the current value and desired value can be within acceptable tolerance.

The solutions in this work have a similar goal to the discussed performance-measurement systems, with a few differences. Unlike Kaplan's (1984) BCS, this design method links top-level financial metrics to performance metrics in a top-down decomposed hierarchy, versus a horizontal hierarchy related to different perspectives. Similar to Lynch and Cross's (1991) SMART pyramid, the design method in this work uses a top-down decomposition hierarchy from the top financial metrics down to the performance-level metrics that control them. Unlike the SMART pyramid, the design solutions are intended to include evolution and innovation. Similar to the Performance Prism (Kennerley and Neely 2000), FMs are used to track how well the system is performing as well as to facilitate communication about strategy and incentivize implementation of the strategy. Unlike the Performance Prism, which states that metrics should be derived from customer wants instead of from strategy, the FMs in this work are derived from strategy.

The solutions in this work use a top-level metric similar to Suh (2001) and Cochran’s (2002) ROI based decomposition and, in some cases, have the same children. Unlike Suh (2001) and Cochran (2002), the order acceptance design solution uses the ROI equation (Phillips 1997):

$$ROI = ((gain - cost) / cost)$$

Similar to Cochran's (2013) CSD, the critique of the first design solution explores the use of physical metrics for DPs. A physical metric (PM) is defined as the adjustable dimension of a DP. Similar to Suh’s (2001) ROI decomposition and unlike Cochran’s (2002 and 2013) works, FMs are decomposed to determine the next level of FMs with FR DP pairs assigned to control them. Also, unlike Cochran’s (2002) MSDD, which inspires much of this work, this method uses FMs at every level instead of just at the top-levels.

The solutions in this work use axiomatic design with some differences. Similar to Suh (1990), this method uses FRs and DP pairs to independently control the functions within the system. This work is unlike the majority of recently published work on decompositions within the axiomatic design community, which appear to use the zig-zag FR DP decomposition method without FMs. Each FM has an explicitly defined SDE or formula of lower-level FMs that combine to equal the parent, similar to Suh’s designs in his textbooks (Suh 1990, 2001). However, in this work, unlike some of Suh’s designs, physical metrics are not defined for each of the DPs. The next level of FR DP pairs independently controls each variable in the parent FM’s SDE. This continues until the method for obtaining a FM is obvious.

This work uses thematic decomposition to design CEME solutions similar to Dickinson and Brown (2009), who write that themes should be developed when decomposing a solution and used to justify

CEME. This method uses FMs and their SDE as quantitative justification for CEME, in contrast to qualitative justification.

This work features a design solution for increasing the probability of winning football games. This is somewhat similar to the mentioned authors who have written on football and baseball. Similar to Lewis (2004), who writes about determining the correlation between certain baseball metrics and wins, the football design solution attempts to determine which metrics have the highest correlation with winning. However, the design solution attempts to control all of the metrics that contribute to wins, instead of focusing on the most influential. Like Carter (1970), Romer (2006), and Urschel (2011), this design is not risk averse and attempts to maximize point potential over the course of the game, which sometimes requires actions that traditional strategies might deem risky. However, in contrast to these authors, this design looks at decision-making on every down, instead of only at the fourth down.

2. Methods

The methods in this work can be divided into three parts:

(1) Decomposing FMs
(2) Determining actionable FMs
(3) Designing and critiquing three solutions that use FMs

2.1 Decomposing FMs

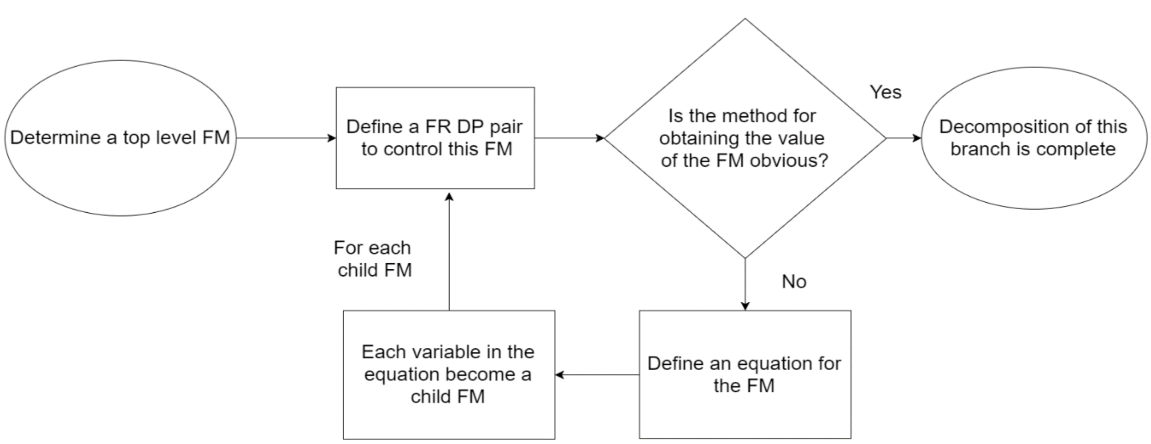


Figure 13: Flow chart for decomposing FMs

A method has been designed for decomposing FMs (Figure 13). Higher-level FMs, which are the parents, are connected to lower-level FMs, their children, by metric formulas or SDEs in which control of the parent is dependent on the children. For example, if a solution is designed to control ROI in a manufacturing company, the top-level FM might be determined to be ROI with a FR DP pair to control it and a SDE:

FR 0: Control ROI

DP 0: Manufacturing system design

FM 0: ROI

The method for obtaining the value of FM 0 is not obvious at this point, and so a SDE could be defined for it:

FM 0: ROI = ((Gain – Cost) / Investment)

There are three variables in the SDE for ROI, "gain," "cost," and "investment." It can be said that ROI is a dependent variable of these three variables. Therefore, if these variables are being controlled, ROI,

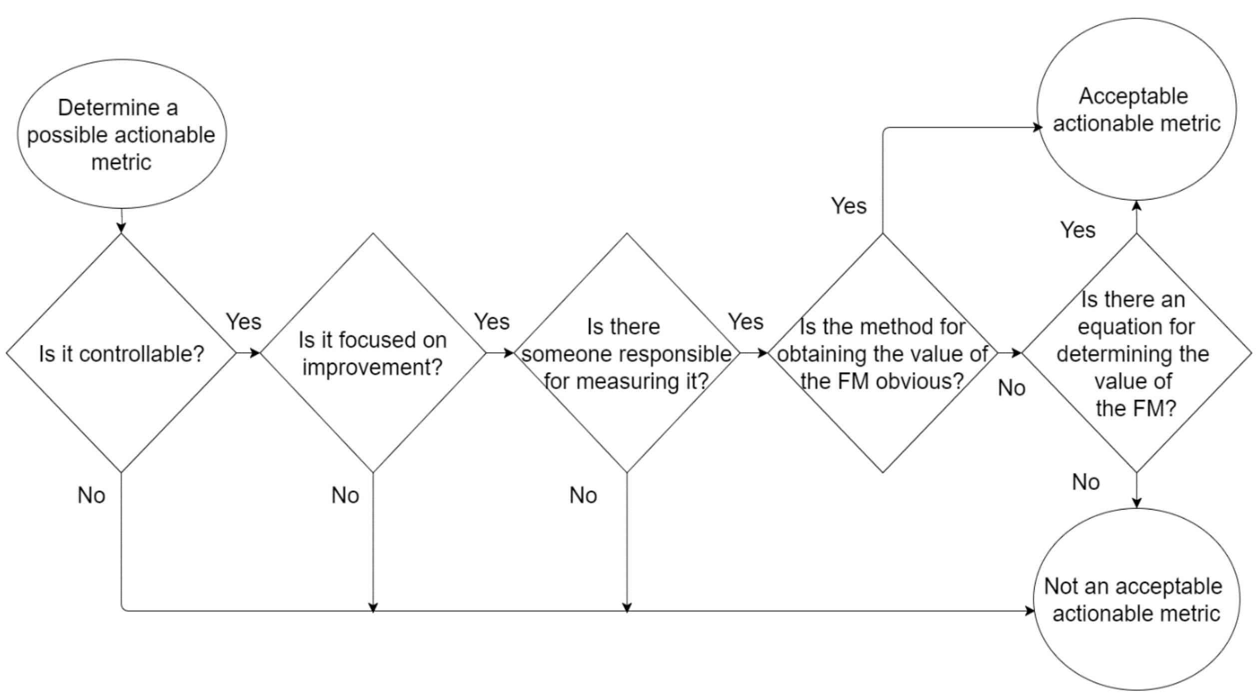


Figure 14: Flow chart for determining actionable metrics

being dependent, is being controlled. These variables become children FMs of the parent FM, ROI:

FM 1: Gain

FM 2: Cost

FM 3: Investment

The process begins again, starting with FM 1 and then FM 2 and FM3, continuing until the method for determining the value of the FMs at the lowest level is obvious.

2.2 Determining Actionable Metrics

A method is designed for determining actionable metrics. Two solutions with the same top-level FM might have lower-level FMs, which might be a result of having different DPs in the solution and therefore different lower-level FMs needing to be controlled. This could also be the result of the resources of the organization limiting what can be measured, or caused by a variety of other reasons. Therefore, when determining which FMs are actionable, there are criteria that must be met (Figure 14).

The goal of a decomposition is to provide the user control of the top-level FM within the solution. If a lower-level FM is not controllable, it should not be a part of the solution, since it will limit the control on the top-level FM. A possible actionable FM should be focused on improvement rather than variance. Making a change in a FM is not useful unless it contributes to the improvement of the organization. There needs to be someone responsible for measuring the FM. This is important because a FM loses value to the organization if there is no active measurement of its value and timely feedback, so that changes can be made as soon as possible when the FM is out of tolerance. The method for obtaining the value of the FM should be obvious, or there should be a explicitly defined SDE or formula that leads to obtaining the value of the FM. A FM loses value the more difficult it is to obtain; therefore, the FM and ways to obtain its value should be simple and straightforward. If a FM meets all of these criteria, it can be considered an actionable FM.

2.3 Designing and Critiquing Three Solutions That Use FMs

Three solutions are designed and critiqued to explore in what ways designing solutions using functional metrics might improve the design process and solutions. The methods used to design these solutions are intended to provide controllable CEME solutions.

The first two solutions are quite similar in function and are explained together in this section. However, they will have their own individual chapters later in this work. The difference between them is the part of the organization that they affect. Each solution is designed to facilitate controlling ROI within an organization. The first solution is for accepting orders during over-capacity situations and is intended to improve the user's ability to control the estimated ROI during an organization's order-acceptance process. The second is a logical solution for managing production processes and is intended to improve the user's ability to control ROI during the production process that follows the order-acceptance process.

The third is a logical solution designed to increase the probability of winning American football games. This solution is intended to reduce the uncertainty in play-by-play decisions and control the metrics that relate to statistics that affect winning games. This is similar to achieving a certain return on investment, since there is a monetary and time-based investment by each team; however, the return is measured in points instead of money.

2.3.1 First Two Design Solutions

For the first two solutions, multiple iterations of each solution during the design process are critiqued for their successes and failures. These iterations are used to test two hypotheses in the context of managing return on investment (ROI): (1) That a meaningful FM assigned to every FR could facilitate the design of CEME systems; (2) That parent FMs should equal the sum of their children. Due to the similarity of these two systems, the first system will be described here to represent both. The difference between the two is the specific FMs at the lower-levels that measure the different lower-level FR DP pairs. These specific iterations each represent a different stage in thinking as the concept of decomposing with FMs evolved.

Over the course of working on these systems, there are three noticeable stages of evolution, which culminate in the use of FMs at every level. Each new stage is born from the difficulty decomposing the previous iteration of the solution to design a CEME solution. Each of the iterations of the design solution is an example of a certain stage. The first stage is decomposing without the use of FMs. The second stage is the use of FMs at the top two levels to provide a structure by which to begin decomposing. This is similar to Cochran's (2002) MSDD, which is both an inspiration for this work and a template for how to begin decomposing solutions. The third stage uses FMs at every level of the decomposition. The FMs are decomposed to determine which children FR DP pairs should be present at each lower-level. This is intended to provide a controllable CEME design solution by providing control of each lower-level metric present in the parent FM's SDE or formula.

2.3.1.1 Iteration 1: Before the Use of Metrics

Each of the iterations is explained and critiqued individually for its successes and failures. As the design progresses through each stage, the failures of the previous design become evident. The struggle with designing each of the iterations and the benefits of using FMs at more levels in each of the subsequent iterations is discussed. The ways in which applying FMs to design solutions might add value are discussed.

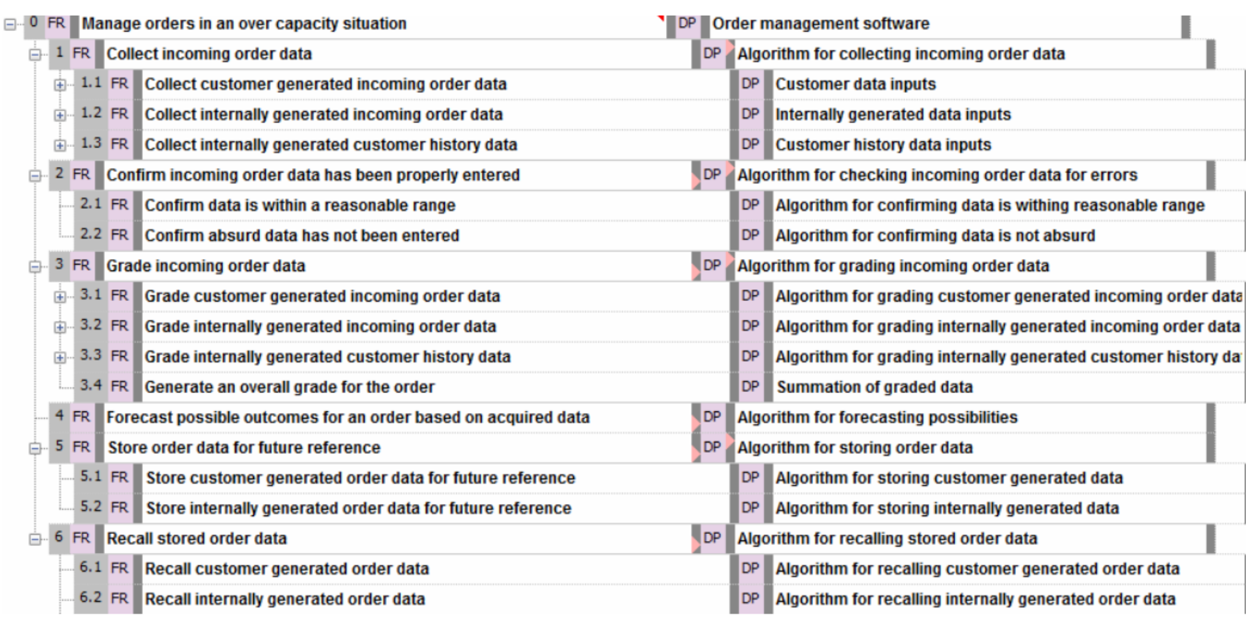


Figure 15: Design solution iteration without FMs (Henley 2015).

This first iteration is decomposed without using FMs during zig-zag FR DP decomposition (Figure 15). CNs are collected over time through multiple iterations with the customer. The customer is defined as the user of the design solution. The top-level FR is:

FR 0: Manage orders in an over capacity situation

An over-capacity situation is defined as a situation is which the resources required by accepting all incoming orders exceed possible resource capacity under normal work conditions. The two top-levels are designed by creating a hierarchy of three main columns into which the CNs could be grouped (Henley 2015):

(1) Evaluate incoming orders [FR 1-3]
(2) Forecast possible outcomes for an order [FR 4]
(3) Store the data for future use [FR 5-6]

However, translating every CN into a FR or DP makes it difficult to design a CEME solution as some CNs might not be relevant to controlling FR 0. There are several failures in this design solution. By collecting lists of customer needs over time, the design solution begins to suffer from what Cochran (2013) calls "requirements soup." This occurs when every new idea becomes a CN with no explanation of where it fits into the current design or the importance of one CN in relation to another. This is exacerbated by not using FMs. If there are FMs with related SDEs or formulas present in the solution, that might facilitate determining where in the solution the new CN belongs and which FR DP pairs it might affect.

In this iteration there is no way to quantitatively measure how effective the design solution is at satisfying the top-level customer need. A cause for this difficulty might be choosing a FR 0 that uses a vague verb. “Manage” might mean different things to different users. Also, without a FM, there is no agreed-upon objective measurement by which to calculate how well the incoming orders are being managed. Establishing a metric might facilitate determining how successfully FR 0 is being satisfied. There are possible FMs that could be determined to measure how successfully the orders are being managed (e.g., percent of incoming orders being managed), but there is still another problem. Managing every order does not necessarily add value to the customer. The value to the customer, who might be the manager of an organization, for example, is in being able to control the long-term health of the organization. This can be accomplished by controlling ROI. Therefore, FR 0 should be related to controlling ROI.

Though this iteration does not provide the desired level of value to the customer, there are several observations that add value to improving the design process. The customer might not necessarily know how to express what is wanted at the lower levels of the design solution but might employ some metric that measures the level of the organization's success. Not knowing exactly what they want, some expressed CNs might not be a necessary part of the solution that controls the top-level metric they measure. There is also the chance that they might overlook expressing CNs to control functions that are necessary for a CEME solution. It seems that starting with a top-level FM might facilitate identifying which CNs should or should not be present in the design, as well as which might have been missed. The observations from this iteration seem to support the hypothesis that using FMs can facilitate designing solutions to control ROI.

2.3.1.2 Metrics at the Top Two Levels

This second iteration uses FMs at the top two levels, similar to Cochran's (2002) MSDD (Figure 16). Using the observations made from the first iteration, a new top-level FR is developed:

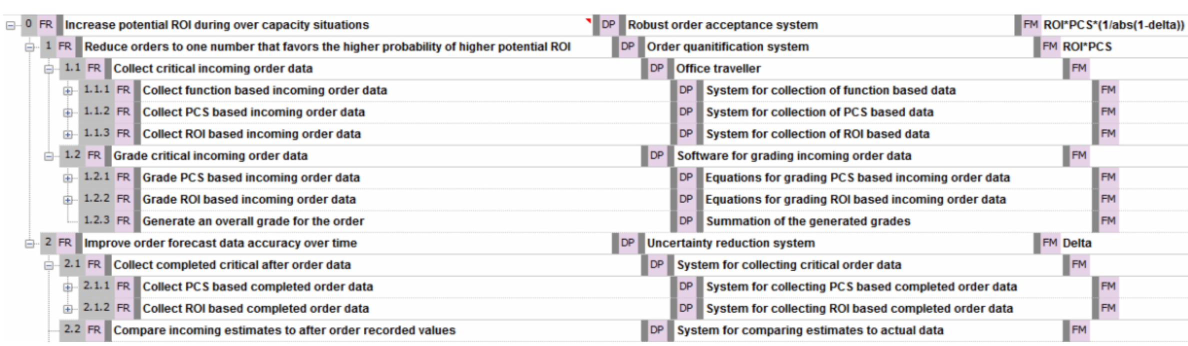


Figure 16: Design solution iteration using FMs at the top two levels (Henley 2015)

FR 0: Increase potential ROI during over-capacity situations

This is an attempt to design a CEME solution using a quantitative decomposition theme. Metrics are used at only the top-levels to reduce information overload (Kaplan 1992). This is a situation that can occur from having too many metrics to monitor. Kaplan writes that managers might benefit by focusing on a few critical metrics. The first two levels of FR DP pairs are determined by the decomposition of the top-level metric. This provides a hierarchy for organizing the lower-level CNs and their related FR DP pairs.

Initially, the top-level FM was ROI, as inspired by Cochran (2002) and Suh (1990). After decomposing FR 0 to the next level, the same way that Suh and Cochran had, it becomes clear that ROI is not a collectively exhaustive top-level FM in this situation. "A metric should be any measure that adds value to the system" (Melnyk 2004).

When an organization receives an incoming order, estimates are provided of the resources required to complete the order. These estimates are made using expert opinion but might differ from the actual resource requirements when completing the order, and so the ROI is more accurately a potential ROI. There is a level of inaccuracy, which if controlled, could add value to the customer. The metric "delta," which is defined as the difference between the estimated and actual costs, should be controlled and preferably minimized.

Controlling this potential ROI is the combination of satisfying several other functions. Timely completion is not a guaranteed outcome. The supplier must determine the resource costs for each incoming order versus the potential gain "ROI". The supplier must provide a product that meets the customer's specifications by the desired time, which is termed "PCS". The supplier must also determine the level of inaccuracy of these resource cost estimates and the likelihood of being able to meet a customer's time and specification requirements. The formula for controlling the top-level metric is therefore determined to be the product of ROI, PCS, and 1/(1+delta), which are the three next level of FMs to be controlled with FR DP pairs:

$$(ROI*PCS) / (1+delta)$$

There are several problems with this iteration. Lower-level CNs are assigned FR DP pairs, which are organized under a hierarchy of either being related to ROI, PCS or delta. However, it is difficult to organize them more specifically than fitting somewhere in one of those three columns. This also makes it difficult to know what necessary functions might be missing from the solution, which should be controlled for a CEME solution. Due to the lack of FMs at the lower-levels, elements like capacity are not considered, even though available capacity logically has an effect on being able to complete an incoming order to specification and on time, with normal effort. From this observation, it can be said that FR 1 must not be CEME. Using FMs at every level might have facilitated identifying a SDE or formula that was not being fully controlled. Another issue is that without FMs lower in the design, if the design solution underperforms, it might be difficult to trace the cause. The contrast between the ease of determining the top-levels of the design versus the difficulty in determining the lower-levels is an encouraging sign that using FMs at lower-levels might facilitate designing a CEME solution. This design supports the hypothesis that children FMs should sum to equal their parent, at least one level down.

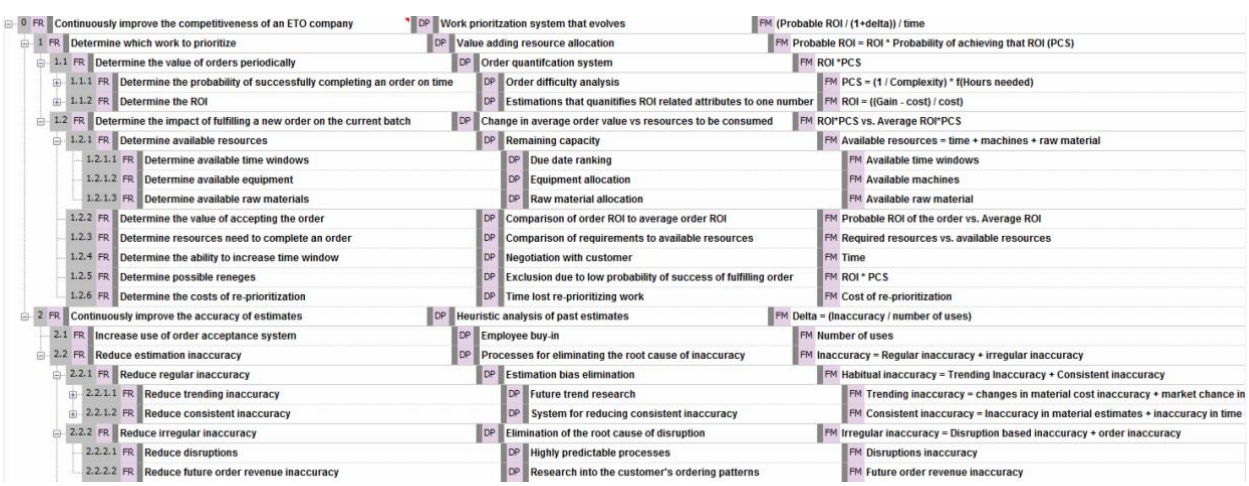
2.3.1.3 Metrics at Every Level

This third iteration features FMs with FR DP pairs to control them at all levels (Figure 17). The top-level FM is determined using the observations from the two previous iterations:

FR 0: Continuously improve the competitiveness of an ETO company

FM0: (Probable ROI / (1 + delta))/time

(**Probable ROI / (1 + delta))/time** was chosen as the top-level FM, similar to the previous iteration. Probable ROI is the product of ROI and PCS. Delta is used in the same way as in the previous iteration.



	FR		DP	FM
0	FR	Continuously improve the competitiveness of an ETO company	Work prioritzation system that evolves	(Probable ROI / (1+delta)) / time
1	FR	Determine which work to prioritize	Value adding resource allocation	Probable ROI = ROI * Probability of achieving that ROI (PCS)
1.1	FR	Determine the value of orders periodically	Order quantifcation system	ROI *PCS
1.1.1	FR	Determine the probability of successfully completing an order on time	Order difficulty analysis	PCS = (1 / Complexity) * f(Hours needed)
1.1.2	FR	Determine the ROI	Estimations that quanitifies ROI related attributes to one number	ROI = ((Gain - cost) / cost)
1.2	FR	Determine the impact of fulfilling a new order on the current batch	Change in average order value vs resources to be consumed	ROI*PCS vs. Average ROI*PCS
1.2.1	FR	Determine available resources	Remaining capacity	Available resources = time + machines + raw material
1.2.1.1	FR	Determine available time windows	Due date ranking	Available time windows
1.2.1.2	FR	Determine available equipment	Equipment allocation	Available machines
1.2.1.3	FR	Determine available raw materials	Raw material allocation	Available raw material
1.2.2	FR	Determine the value of accepting the order	Comparison of order ROI to average order ROI	Probable ROI of the order vs. Average ROI
1.2.3	FR	Determine resources need to complete an order	Comparison of requirements to available resources	Required resources vs. available resources
1.2.4	FR	Determine the ability to increase time window	Negotiation with customer	Time
1.2.5	FR	Determine possible reneges	Exclusion due to low probability of success of fulfilling order	ROI * PCS
1.2.6	FR	Determine the costs of re-prioritization	Time lost re-prioritizing work	Cost of re-prioritization
2	FR	Continuously improve the accuracy of estimates	Heuristic analysis of past estimates	Delta = (Inaccuracy / number of uses)
2.1	FR	Increase use of order acceptance system	Employee buy-in	Number of uses
2.2	FR	Reduce estimation inaccuracy	Processes for eliminating the root cause of inaccuracy	Inaccuracy = Regular inaccuracy + irregular inaccuracy
2.2.1	FR	Reduce regular inaccuracy	Estimation bias elimination	Habitual inaccuracy = Trending Inaccuracy + Consistent inaccuracy
2.2.1.1	FR	Reduce trending inaccuracy	Future trend research	Trending inaccuracy = changes in material cost inaccuracy + market chance in
2.2.1.2	FR	Reduce consistent inaccuracy	System for reducing consistent inaccuracy	Consistent inaccuracy = Inaccuracy in material estimates + inaccuracy in time
2.2.2	FR	Reduce irregular inaccuracy	Elimination of the root cause of disruption	Irregular inaccuracy = Disruption based inaccuracy + order inaccuracy
2.2.2.1	FR	Reduce disruptions	Highly predictable processes	Disruptions inaccuracy
2.2.2.2	FR	Reduce future order revenue inaccuracy	Research into the customer's ordering patterns	Future order revenue inaccuracy

Figure 17: Design solution iteration using FMs assigned to FRs at all levels (Henley 2015)

Each new level of the design solution is determined by the SDE or formula for the FM. In this case, (**probable ROI / (1 + delta))/time** is the top-level FM, and so the next level needs two FR DP pairs, one to control **probable ROI** and another to control **delta**. Time is not a variable to be controlled in this situation. It only implies that the value of this FM over time is being measured.

This process of decomposition is repeated at every level. The FM for FR 1 is **probable ROI = ROI * PCS**.

FR 1: Determine which order to prioritize

FM 1: Probable ROI = ROI * PCS

This, similar to the level above, means that the next level should have two FR DP pairs, one to control **ROI** and one to control **PCS**. This decomposition cycle should only end when either the FM no longer has a necessary SDE or formula, which is the combination of other FMs, or when the method for obtaining the value of the FM is obvious.

This decomposition provides value to the customer by providing a method for independent control of every FM at the lower-levels and as a result, control of the top-level FM. Also, there is value added to the customer by providing a method for tracing the root cause of underperformance in the system. Even more than in the previous iteration, this adds value to the customer by determining which processes should and should not be allocated resources within the organization, as it relates to the effect on the top-level goal. This could further add value by identifying any coupling within the system due to any possible overlap of FMs within the SDEs or formulas.

Current findings indicate this design iteration could be close to being a CEME system. There is room for improvement for tracing root causes of underperformance to DPs. Assigning physical metrics (PMs) to each DP could facilitate this analysis. PMs might decompose the same way that FMs do, so that the combination of the children equals the parent. This would be in contrast to the current method in this work, having a FM with each FR DP pair. Another possible improvement might be using “control” as the active verb in contrast to “increase” or “decrease.” The idea of being able to control the function to achieve any desired value for the FM seems to supercede and include increasing or decreasing the value of the FM. Also, because of the use of FMs at the upper level, it seems that delta could be reorganized as a child of ROI and PCS. This would eliminate what might be partial coupling between FR 1 and 2. This design supports the hypothesis that FMs can facilitate designing a CEME solution. This design solution supports the hypothesis that children FMs should sum to equal their parent.

2.4 Football Design Solution

The third solution being designed is a logical solution to increase the probability of winning American football games. A design solution is developed using metrics from the beginning. Similar to the previous systems, the top-level FM is related to ROI. Also, there is a critique of the system and a comparison to a different decomposition that attempts to control the same top-level FM. Unlike the previous solutions, the ROI in this system is not monetary. Also, unlike the previous two systems, there are no design iterations before the inclusion of FMs in the design process and solution.

Unlike the previous design solutions, the level to which FMs are featured is equal in each of the decompositions. Also, unlike each of the different iterations in the previous design solutions, both of the decompositions in this design solution have the same top-level metric. Instead, the differences are the FMs, SDEs and formulas used to decompose the solution.

The design solution decomposed in this work is compared to a different decomposition by a different designer, using the same top-level metric and design process, and both will be critiqued. Different designers decomposing the same system might have different opinions about what the lower-level FMs should be present to control the top-level FM, in this case:

FM 0 = Average point differential

Likewise, the SDEs or formulas for the same FM might be different when considered by different designers. Both decompositions use “average point differential” as the top-level FM. Point differential is defined as the difference in points scored by the ally team and those scored by the opposing team over the course of a game. However, the SDEs and formulas generated for the FMs at lower-levels of the decompositions differ, and, as a result, so do the FR DP pairs. A football simulator is used to test both decompositions against each other. The weaknesses and strengths of both of the decompositions relative to and independent of each other are discussed.

The design solution designed in this work is also being compared to traditional strategies used by football coaches who are not familiar with axiomatic design. The same football simulator is used to compare the decomposition in this work against these traditional methods. The strength and weaknesses of this system relative to and independent of traditional methods is discussed. How this design solution might add value to a football organization versus using tradition methods is examined.

The work then compares the difference between designing the first two design solutions and the design solution for winning American football games. Ways in which using metrics in the design process might add value by facilitating the design of CEME solutions with fewer iterations is also discussed.

3. Concluding Remarks

These methods could impact AD's decomposition process and could provide a quantitative justification for determining CEME, if all of the variables within the FM's SDEs and formulas are being independently controlled. First, this could improve effectiveness and ROI of a design solution as has been discussed in this work. Second, this could improve the efficiency of the design process. Using zig-zag decomposition without FMs can often take multiple iterations to arrive at what is believed to be a CEME solution. Using FMs when decomposing could facilitate determining the next level of FR DP pairs. This could reduce the number of iterations required to arrive at a CEME solution, improving the ROI of the design process.

The first design solution discussed in this work has been published and presented at the 2015 International Conference of Axiomatic Design (ICAD) in Florence, Italy. The methods have changed since then, specifically regarding the active verbs within the decomposition. In the publication, the active verbs were often "increase" or "reduce" and now "control" is the preferred active verb. The third solution related to football has been published and presented at the 2016 ICAD in Xi'an, China.

There are two research questions that would be valuable to answer, even if not in this work:

1. How can this system be applied outside of the context of controlling ROI?
2. If two designers use the same top-level FMs, DPs, and organization with the same resources but have unique lower-level metrics, can a difference in value of the solution be measured, and can the individual value of the metrics be measured?

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Chapter 2: Using functional metrics to facilitate designing "collectively exhaustive mutually exclusive" systems in the context of managing return on investment

1. Introduction

The objective of this paper is to test two hypotheses in the context of controlling return on investment (ROI):

(1) That a meaningful functional metric assigned to every functional requirement (FR) could facilitate the design of collectively exhaustive mutually exclusive (CEME) systems.

(2) That parent functional metrics should equal the sum of their children.

In this paper, metrics are defined as quantifiable measures used to determine the degree of success of a system or process. A functional metric (FM) indicates how well a FR satisfies a customer need (CN). A physical metric (PM) is defined as the adjustable dimension of a design parameter (DP) responsible for controlling a FR. This paper is inspired by a work-in-progress design that has been satisfactorily unsuccessful to date at decomposing a quantitative CEME system. Metrics were intended to be assigned to each FR and DP. It is worth noting that "manage ROI" was chosen over "maximize ROI" in the objective. Suh (2001) and Cochran et al. (2002) use maximize as the verb in FR 0. Thompson (2013) writes that maximize is selection criteria when choosing between possible DP options. Maximizing ROI without a specified time interval can be harmful to a company. Actions taken to maximize short term ROI can hurt long term ROI. Manage can be a more appropriate verb when there might be times that accepting a lower ROI in one time interval to increase ROI in another can be in the company's best interest.

1.2 Rationale

"If a system or process cannot be measured then it cannot be objectively improved" (Lord Kelvin). A system with metrics can be compared against benchmarks. These benchmarks can be measurements of some previous state of the system, a desired goal, or best in class measurements of a competitor. Without being able to quantitatively measure the metrics at a system's current state, it cannot be objectively determined whether the system is improving or the amount of improvement.

Having FMs in a system can facilitate translating CNs into the subsequent domains. Axiomatic design begins with the customer domain. Customers express ideas that become CNs, which they require in a process or system (Suh 2001). When meeting with customers over time, new CNs can be expressed late in the design phase. Cochran et al. (2013) writes how this can leave a design susceptible to "requirement soup." This occurs when every new idea becomes a CN with no explanation of where they fit into the current design or the importance of one CN in relation to another. Having metrics at every level can facilitate determining where CNs belong in a design, regardless of when the CN is expressed during the design phase, by what metrics they affect.

Without metrics at every level, when the system is underperforming, it can be difficult to trace the cause (Austin 2013). An integral part of continuous improvement should be identifying and removing the root cause of dysfunction in the system. FMs at every level can facilitate identifying the cause of dysfunction.

Metrics at every level can improve long term ROI. By measuring only financial metrics at the executive level, focus is placed on efficiency. Innovation processes, which can have a negative short term effect on ROI but potentially improve long term ROI, can be avoided as a result (Kaplan et al. 1984). By having FMs at every level, focus is place upon efficiency and effectiveness (Richardson et al. 1980).

1.3 State of the Art

Brown (2011) writes that a good hierarchical decomposition must be CEME. CEME meaning "mutually exclusive, collectively exhaustive" is a method designed for facilitating the framing of a problem. The goal is to reduce the parts of a problem to non-overlapping issues to prevent leaving out relevant issues (Rasiel 1999). Axiomatic design evolved this method into CEME min, which uses the minimum number of FRs while remaining collectively exhaustive and mutually exclusive (Dickinson et al. 2009).

The use of metrics to measure the success of systems is not a new phenomenon. Until recent decades however, the focus has been on measuring top level financial metrics with little measurement at the performance level. Bruns (1998) writes that for centuries the level of a system’s success has been based on financial metrics. An important milestone was the creation of the return on investment metric by

DuPont in 1912. Kaplan et al. (1984) writes that almost all of the practices for measuring cost and financial success were developed by 1925. Since then, there were no major innovations in performance metrics until the 1980s. Due to the competitive manufacturing environment of the 1980s, there became a growing belief that top level financial metrics alone were not sufficient for improving or controlling systems (Johnson et al. 1987).

As a result, organizations began investing effort into developing performance measurement systems. The most commonly used system was the balanced scorecard (BSC) [13, 14]. This system was designed to link what was determined to be the four important perspectives in a business: financial, customer satisfaction, innovation and performance. Each perspective has multiple goals within, and each goal has functional metrics to be measured. Kennerley et al. (2003) write that data gathered by the Balanced Scorecard Collaborative suggest that over fifty percent of the largest businesses in the USA adopted the BSC by the end of 2000.

Another system worth noting is The Strategic Measurement and Reporting Technique (SMART) pyramid (Lynch et al. 1992). Unlike BSC, SMART was designed as a performance measurement system that decomposes corporate objectives down to lower level goals versus viewing metrics by perspective. The system links performance metrics to top level metrics, prioritizes both efficiency and effectiveness but excludes continuous improvement (Susilawati 2013).

Even in professional sports, lower level performance metrics have been linked to traditionally measured top level metrics to improve the level of success of the top level function. Lewis (2004) writes about the failure within professional baseball to identify the right metrics. For decades, teams had bought players in an attempt to increase wins using statistics such as batting average and runs batted in. Statistical analysis showed that on base percentage had a higher correlation with runs scored, which in turn determines wins. With this information, the 2002 Oakland Athletics were able to win the most games of any team in the league during the regular season, despite paying the third lowest salary to their roster. They also broke the American League record for most games won in a row at 20 wins.

Metrics have been used in axiomatic design previously. Suh (2001) gives many examples in his book of decompositions with metrics for the FRs and DPs. One simple example is a hubcap design in which the FR is retention force and deflection is the DP. Even though he only writes of it in respect to the FR design range for determining the DP design range, the force of retention can be measured as a FM. Similarly the deflection can be measured as a PM.

In the context of ROI, Suh (2001) proposed that ROI can be decomposed to three main FRs: (1) increase sales revenue, (2) minimize cost and (3) minimize investment. His design decomposes the functional metric equation for FR 0, ROI = (Sales - Cost / Investment). The next level of FRs and DPs are used to control each variable in the equation independently. Manufacturing System Design Decomposition (MSDD) was similarly designed using the same 3 three top level FRs as Suh (2001) used to satisfy the goal of maximizing return on investment (Cochran et al. 2002). Collective System Design (CSD) is a method based on axiomatic design theory (2013). This system provides a behavior and process for collective agreement during a company's conversion to lean, to achieve long term sustainability. This includes assigning metrics to FRs and DPs.

1.4 Approach

Three attempts were made to design an order acceptance system using axiomatic design. This is a system for deciding which orders a engineer to order (ETO) manufacturing company should prioritize working on, when the workload exceeds the available capacity. The company's goal is to achieve the highest potential ROI. For these design attempts, the ETO company is considered the customer. Each attempt has been unsuccessful at designing a quantitatively justifiable CEME system. Each design attempt iteration increasingly features FMs to facilitate and add value to the design. The process for each design attempt will be explained. The possible reasons for failure in each design attempt will be discussed. It will be discussed whether the attempts support or refute the paper's hypotheses.

Similar to BSC and SMART, the design attempts feature FMs. Unlike BSC, a top down hierarchy is used. Similar to SMART, the design attempts decompose higher level metrics from the top level financial metrics down to the lower level performance FMs. However, the design attempts include continuous improvement.

The design attempts are similar to Cochran's (2002) MSDD method and similar to Suh's (2001) ROI decomposition method. However, the current method uses a different equation ((gain - cost) / cost) (Phillips 2007). Also unlike their systems, the third attempt has FMs to be measured at each level versus the top levels.

Similar to Brown (2011) and Dickinson et al. (2009) each design is an attempt at a CEME system. Unlike in their works, the approach in the third design attempt provides a metric based method for designing CEME decompositions. Parent FMs appear as mathematical equations or expressions. These FMs decompose into children FMs which independently control each variable in the equation or expression. This process will continue down to lower level independent variables. FR DP pairs are designed to control each FM independently. This method serves as a quantitative justification for CEME.

2. Design Attempts

2.1 FRs and DPs with no metrics

This decomposition (Figure 1) was done before the use of FMs, which were added later. FR 0: "Manage orders in an over capacity situation". The first level was designed using a theme based on three customer needs: (1) evaluate incoming orders [FR 1-3] (2) forecast possible outcomes for an order [FR 4] (3) store the data for future use [FR 5-6]. There was difficulty designing a system in which every CN translated to a FR or DP while remaining CEME.

This decomposition was the result of collecting multiple lists of customer needs over time and suffered from "requirements soup." Also, even though this system was designed to manage orders, there is no way to tell how successful the order management software is at satisfying FR 0. Choosing a FR 0 that does not have an indicated preference for which direction it should go in is likely a cause for difficulty with this design. Having a metric would facilitate determining how successfully FR 0 is being satisfied. A possible logical FM for this FR 0 might be the percent or number of orders being managed, but this does not add much value to the customer.

The value to the customer is not in the managing of orders, but instead in increasing ROI. The order management software is the tool for doing so. Increase or control ROI might be a better FR 0 with the order management software / system as DP 0.

This design led to several observations. The customer does not necessarily know how the full decomposition should look, but they might have a metric they internally measure. As a result, they might request needs that they believe affect the top level metric but in fact do not. Also, the customer might fail to request necessary parts of CEME system. Using a top level functional metric could facilitate determining whether requested CNs should be a part of the design and if there are missing FRs that belong in the design.

The observations made from this design support the first hypothesis that FMs could facilitate designing systems to manage ROI.

2.2 Functional metrics at the top levels

This decomposition (Figure 2) was made using FMs at the top two levels. FR 0: Increase potential ROI during over capacity situations. This was an attempt to design a CEME system, using a quantitative decomposition theme, without causing information overload. Kaplan et al. (1992) writes that information overload can result from having too many metrics to monitor. He writes that managers might benefit by having a few critical metrics to focus on. The top level FRs were determined with the goal of controlling the top level metrics. The lower level FRs and DPs were translated from customer needs.

The top level metric was initially ROI. After decomposing FR 0 down one level, it became clear that ROI was not a collectively exhaustive top level metric. Melnyk et al. (2004) writes that a metric should be any measure that adds value to the system. ROI was not the only value adding metric in this system.

When an ETO company receives an incoming order, they make estimates on how long tasks will

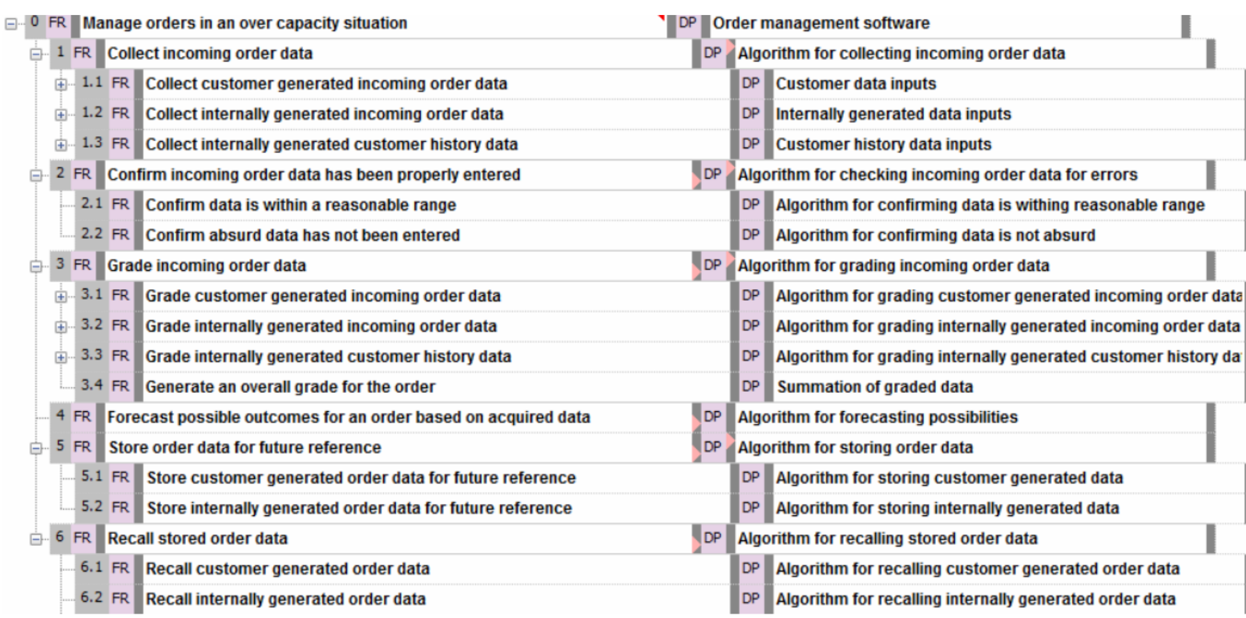

Figure 2 Design attempt that suffers from "requirements soup."

take and what the costs will be. These estimates are made using expert opinion and are likely to differ from the actual costs during the manufacturing process. Reducing "delta," which is defined as the difference between the estimated and actual costs provides value.

Achieving the potential ROI is contingent upon being able to both successfully fill the order and deliver the product on time (PCS). Successful completion is not a guaranteed outcome. The value of an order changes with the change in the probability of achieving the potential ROI. There is value in knowing that probability. The top level metric was adjusted to be the product of ROI, PCS and 1/(1+delta).

When an ETO company receives an incoming order, they make estimates on how long tasks will take and what the costs will be. These estimates are made using expert opinion and are likely to differ from the actual costs during the manufacturing process. Reducing "delta," which is defined as the difference between the estimated and actual costs provides value.

While decomposing the lower levels, there was no clear theme due to not using lower level FMs that make up the ROI, PCS and delta terms. Because of this, elements like capacity were not considered, even though, in retrospect, capacity is a necessary consideration when accepting an order. FR1: "Reduce orders to one number" was considered acceptable at the time. Using FMs at every level, it would have been obvious that focusing solely on reducing orders to one number as the way for improving ROI was not CEME. Another issue in this design is that if only top level metrics are measured, there is no way of knowing the cause of dysfunction if the system underperforms as Austin (2013) wrote.

These findings led to the hypothesis that having FMs at every level could facilitate designing systems to manage ROI. This design supports the hypothesis that children FMs should sum to equal their parent one level down. This design neither supports nor refutes the hypothesis at the lower levels of the decomposition.

0	FR	Increase potential ROI during over capacity situations	DP	Robust order acceptance system	FM	ROI*PCS*(1/abs(1-delta))
1	FR	Reduce orders to one number that favors the higher probability of higher potential ROI	DP	Order quanitification system	FM	ROI*PCS
1.1	FR	Collect critical incoming order data	DP	Office traveller	FM	
1.1.1	FR	Collect function based incoming order data	DP	System for collection of function based data	FM	
1.1.2	FR	Collect PCS based incoming order data	DP	System for collection of PCS based data	FM	
1.1.3	FR	Collect ROI based incoming order data	DP	System for collection of ROI based data	FM	
1.2	FR	Grade critical incoming order data	DP	Software for grading incoming order data	FM	
1.2.1	FR	Grade PCS based incoming order data	DP	Equations for grading PCS based incoming order data	FM	
1.2.2	FR	Grade ROI based incoming order data	DP	Equations for grading ROI based incoming order data	FM	
1.2.3	FR	Generate an overall grade for the order	DP	Summation of the generated grades	FM	
2	FR	Improve order forecast data accuracy over time	DP	Uncertainty reduction system	FM	Delta
2.1	FR	Collect completed critical after order data	DP	System for collecting critical order data	FM	
2.1.1	FR	Collect PCS based completed order data	DP	System for collecting PCS based completed order data	FM	
2.1.2	FR	Collect ROI based completed order data	DP	System for collecting ROI based completed order data	FM	
2.2	FR	Compare incoming estimates to after order recorded values	DP	System for comparing estimates to actual data	FM	

Figure 3: Design attempt using FMs at the top two levels.

2.3 Functional metrics for every FR

This design (Figure 3) has been decomposed with FMs assigned to FRs at all levels. FR 0: Continuously improve the competitiveness of an ETO company. PMs have not been assigned in this design but will be attempted in a future iteration. Probable ROI / (1 + delta) was chosen as the top level FM from what was learned in earlier designs. Probable ROI is the product of ROI and PCS.

Current findings indicate that FR 1.2 and its children are necessary parts of a CEME design. However, FR 1.2 is not decomposing as cleanly as the other parts of the design. Each attempt to re-organize them reduces the number of outlying children, and so it is likely that the children of FR 1.2's correct place in the decomposition just has not been determined yet. Other than FR 1.2, all the children FMs sum to equal the parents.

This decomposition provides value to the customer by offering independent control of each variable that at the lower levels that affect the top level metric. Also, there is value to a customer if the system facilitates tracing the root cause of underperformance; having FMs at every level provides this.

Current findings indicate this design iteration could be close to being a CEME system; however, there is room for improvement for tracing root causes of underperformance to DPs. If the FRs are not being controlled within the acceptable range, it could facilitate tracing the root cause to the DP.

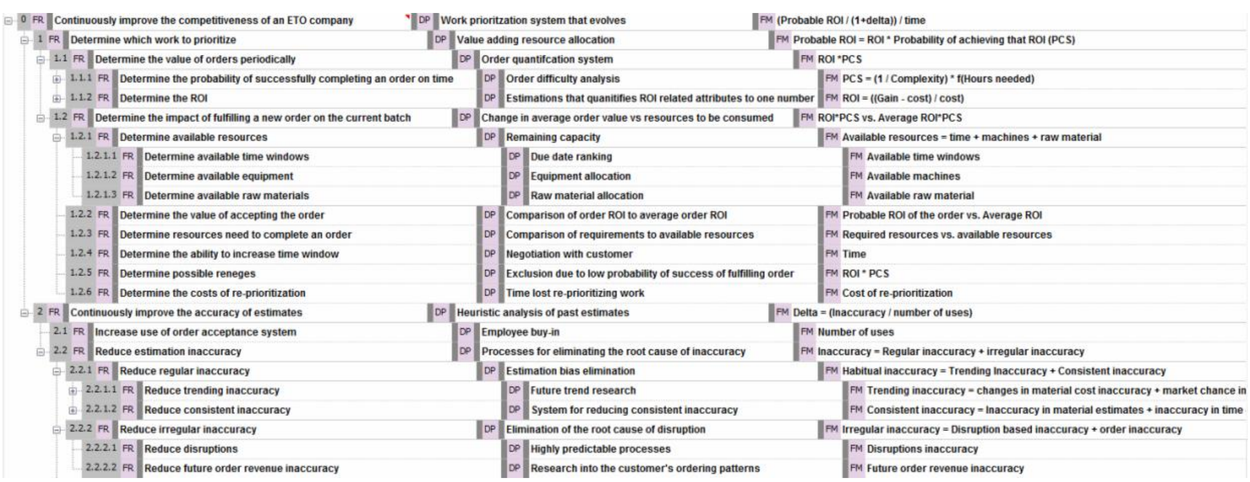

Figure 4: Design attempt with FMs assigned to FRs at all levels (See appendices “Figure 1” for a larger version)

This design supports the hypothesis that FMs can facilitate designing a CEME system. This design supports the hypothesis that children FMs should sum to equal their parent.

3. Discussion

The current findings indicate that FMs at every level of the design can facilitate designing a quantitatively CEME system. FMs have been used in the third design attempt to decompose a CEME system. Each level of FMs is determined using the FM from the level above. Each child FM controls a variable from the parent FM equation or expression. This can be repeated down to lower level independent variables or until the method for determining those variables is obvious. It is unclear how well this would work outside the context of managing ROI.

The current findings indicate that children FMs should sum to equal the parent, if sum is defined as combine instead of solely as addition. This has been an understood concept in previous works dating back to Suh (2001) and Cochran et al. (2002), seeing as their top level equation features subtraction and division. However when talking quantitatively, to avoid confusion, it might be more accurate to say that the children combine to equal the parent.

Other designs might use FMs at the top level inherently. Suh's (2001) decomposition of ROI and Cochran's (2002) MSDD are designed using the equation for ROI = ((Sales - Cost) / Investment). They use ROI as the FM for FR 0 and the variables in the equation as the FMs for the top level FRs, even if they don't directly mention metrics. Cochran's (2014) CSD is an example of a system that assigns FMs and PMs to the top level FRs and DPs as well as at lower levels where needed.

Suh (1990) states that FR = f(DP). The same comparison might be used for FM = f(PM). Suh's (2001) faucet design provides independent control of temperature and flow. This design uses FMs and PMs for FRs and DPs 1 and 2 respectively. Flow (Q) = f(Angle of rotation of faucet handle 1) and Temperature (T) = f(Angle of rotation of faucet handle 2), and so the functional relation between FM and PM might hold true. There is no top level FM or PM that is the sum or product of the lower level FMs and PMs, yet it is considered CEME.

It is possible that for systems, like those that use ROI, in which the top level FM trending in one direction or the other is considered positive or negative, a top level metric to monitor the system's overall trend might be important. However in a system like the faucet, the flow increasing or decreasing is not necessarily considered negative or positive, and so a top level FM might not be as important.

Cochran's (2014) paper states that PMs are often binary. A binary PM measures whether or not there is a DP implemented to satisfy the FR. A binary PM might not be the best choice of PM for a DP. A non-binary PM would measure how well the DP satisfies the FR, which might be a more valuable measurement. If some PMs can be binary and some are not then the sum of children PMs might not equal the parent.

PMs might be a useful tool to facilitate determining the next level of the decomposition. If a FR was "control deflection in the structure, then the FM might be the amount of deflection. The DP could be "beam" and the PM might be the beam length or the elastic modulus, both of which are dimensions of a beam affecting deflection (Deflection = f(length) and deflection = f(elastic modulus)). This might be an indication that the FR DP pair should be decomposed again to measure each PM.

FMs and PMs might be interchangeable. Labor cost = f(Hours), but hours could be used as a FM just as easily due to the obvious relation between labor cost and labor hours.

Lord Kelvin's quote could be applied to determining CEME in a design. Is it possible to be certain of CEME at any level of a decomposition without a quantitative top level metric as the theme? Using FMs for every FR and decomposing that FM as the theme for the next level of FRs provides a quantitative basis for determining appropriate lower level FRs and maintaining CEME. Without a quantitative justification, claims of a CEME system might be guesses.

4. Conclusions

The current findings indicate that FMs at every level of the design can facilitate designing a quantitatively CEME system. FMs have been used in the third design attempt to decompose a CEME system. Each level of FMs is determined using the FM from the level above. Each child FM controls a variable from the parent FM equation or expression. This can be repeated down to lower level independent variables or until the method for determining those variables is obvious.

The current findings indicate that children FMs should sum to equal the parent, if sum is defined as combine instead of solely as addition. This has been an understood concept in previous works dating back to Suh (2001) and Cochran (2002), seeing as their top level equation features subtraction and division. However when talking quantitatively, to avoid confusion, it might be more accurate to say that the children combine to equal the parent.

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Chapter 3: Axiomatic Design applied to play calling in American football

1. Introduction

American football provides an interesting opportunity to test the use of axiomatic design to create a game strategy. It is a highly structured game composed of a series of short precisely predefined and well-rehearsed "plays" where each player has a specific task. In between these plays the players and coaches can consult on the next play to call. The players line up in special formations before each play. Play calling strategies are designed here and tested in game simulations.

This work tests the utility of functional metrics (FMs) and the use of parent-child equations for guiding the decomposition of a design for winning games. The hypothesis is that controlling appropriate FMs can increase the likelihood that a team can outscore their opponent. The scope of this paper is designing play calling in American football games. In a more general sense it is applicable to other games and situations that rely on scores to determine success. For more on scoring and ball control in American Football see Appendix 1.

Metrics here are used to determine the degree of success of a system or process. An FM indicates how well a functional requirement (FR) satisfies a customer need (CN). Parent FMs relate to their children through parent-child equations that are expressed between all levels of the decomposition hierarchies. Upper-level FMs can be considered dependent variables, and the children FMs are the independent variables that combine to equal parent FMs (Henley 2015).

1.2 Rationale

FMs can be important for several reasons. Having FMs at every level can facilitate a decomposition that satisfies axiom one by being collectively exhaustive mutually exclusive (CEME) (Brown 2011). CEME means that the children are collectively exhaustive with respect to the parent and mutually exclusive with respect to each other. CEME applies to decompositions in all domains. Having an FM and a parent-child equation for each FR and design parameter (DP) provides a quantitative path for the determining children FR-DP pairs.

Without being able to quantify a system's current state, it cannot be objectively determined whether the system is improving or the amount of improvement (Henley 2015).

When the system is underperforming, it can be difficult to trace the cause without FMs (Austin 2013). An evolving design solution must be able to identify and adjust underperforming elements within the solution. FMs at every level can facilitate identification and adjustment of underperforming elements.

NFL (National Football League) teams currently invest resources apparently to prioritize metrics that are not the best indicators for winning games. Certain positions on the field are considered more important for achieving certain metrics and can be given a larger percentage of the salary allotment, which is capped by the league.

There can be times when internal or external factors cause certain FMs within the design solution to no longer be as beneficial. This might be a result of reaching maximum capability or because the opponent has made an adjustment that your design solution is not well adapted to handle. A regular review and possible alteration of the design solution can prevent obsoletion of the design solution.

The techniques for the development of strategies and tactics for play calling in American football might also be applied to developing strategies and tactics for other sports and for business and government or military applications as well.

1.3. State of the Art

Due to the competitive manufacturing environment of the 1980s, organizations began investing effort into developing performance measurement systems that measured the effectiveness of the organization’s processes (Bruns 1998). The performance-measurement record sheet (Neely 1997) provides a list of criteria that must be present for a metric before it can be considered actionable.

Lewis (2004) writes about the failure within US Major League Baseball to identify the right metrics. The 2002 Oakland Athletics were able to win the most games of any team in the league during the regular season, despite paying the third lowest salary to their roster by prioritizing metrics that correlate more strongly with wins.

Decision-making in football has been analyzed based on the expected point value (EPV) (Carter et al. 1971, Urschel et al. 2011). The EPV is based largely on the position on the field and is in fact the amount of points a team should be expected to score on average by having a first down at the current field position. This was developed by Carter et al. (1971) by analyzing data from the 1969 NFL regular season. With an EPV of 0 at one’s own 20 yard line, EPV increases roughly 1 point per 18 yards and can also be valued negatively, with a value of -1.25 at one’s own 5 yard line (Romer 2006). A common theme in the literature is that decision-makers for most teams during a game tend to be risk-averse in 4th down situations, to the point of reducing their chance to win. This is due to making play calling decisions that reduce to total EPV over the course of the game (Carter et al. 1971, Urschel et al. 2011).

Suh (2001) gives many examples of decompositions with metrics for the FRs and DPs. He proposed that ROI (return on investment) can be decomposed to three main FRs: (1) increase sales revenue, (2) minimize cost and (3) minimize investment. His design decomposes the FM equation for FR 0, ROI = (Sales-Cost/Investment). The next level of FRs and DPs are used to control each variable in the equation independently. Manufacturing System Design Decomposition (MSDD) was similarly designed using the same 3 three top level FRs as Suh (2001) to satisfy the goal of maximizing return on investment (Cochran 2002). Collective System Design is a method based on axiomatic design (AD) theory (Cochran et al. 2016). This system provides a behaviour and process for collective agreement during a company's conversion to lean, to achieve long term sustainability. This includes assigning metrics to FRs and DPs.

An initial design solution can adapt through a regular review and adjustment of the FMs to ensure that the design solution continues to be valuable. This kind of adapting design solution can save an organization the expense of having to develop a new performance measurement system (Kennerley et al. 2002). The performance paradox model (Meyer et al. 1994) explains the inevitable need for evolution as a requirement in every performance measurement system. A new set of metrics will need to be defined that measure the same value to the customer if the success rate of current solution becomes stagnant or moves in an undesired direction.

According to Cochran et al. (2016) there are three options when the FMs are not acceptable:

(1) Improve the standard work without changing the physical solution (PS)

(2) Determine a new PS

(3) Change the respective FR.

1.4 Approach

Similar to Suh (2001) and Cochran et al. (Cochran 2002), AD is used here as the framework for the two design solutions, initial and adapting. However, unlike those authors, but similar to Henley (2015), they will feature FMs and parent-child equations at every level. Similar to Brown (2011), this design is an attempt at a CEME solution. Unlike his work, FMs and parent-child equations are used as a quantitative method for determining CEME. Similar to Bruns (1998), Suh (2001) and Cochran et al. (2002), ROI is a top level FM for success. However, in this situation the return will be measured in points. Similar to Neely (1997), the performance record sheet is used to determine actionable lower level FMs that control the top level FM. Similar to Lewis (2004), the play calling strategies in this work will prioritize controlling lower level performance related FMs.

The play calling strategies here are intended to maximize the EPV in each game and in each series of plays and minimize the opponent's EPV. Similar to Carter et al. (1971) and Urschel et al. (2011) decisions on 4th down will be made to increase the EPV as opposed to a more risk adverse strategy that tends to favor punting and field goal attempts.

Also, similar to Cochran et al. (2016) and Kennerley and Neely (2002), the design solution must be able to be altered when it is underperforming. Similar to Cochran et al. (2016), the method for addressing an underperforming FM is to first improve the standard work. One example situation might be controlling the metric for the time it takes to rush the quarterback. Improving the standard work could be changing out a player for one who is faster and therefore rushes the quarterback faster. If improving the standard work is not sufficient, the next option is to alter the DP. An example of this could be changing to a play that increases the number of players rushing the quarterback.

Unlike Cochran et al. (2016) who suggests the possibility of defining new FRs as a possibility for improving performance, new FRs are not considered over the course of testing these design solutions. Unlike Meyer and Gupta (1994), who suggest the possibility of defining new metrics as a possibility for improving performance, new metrics are not considered over the course of testing these design solutions.

2. Methods

2.1. Formulating two solutions

Fig. 1 shows the top two levels for the first design solution and FM equations for the third level. Both solutions are designed using axiomatic design and have the same FR0, FM0 and parent-child equations. The difference is that for the second design solution, DP0 is "Adaptive play calling strategy."

The FR is defined to control the related FM, in this case FR0 is outscore your opponent and FM0 is point differential (PD).

The DPs define the scope of the design of the FRs and DPs at the lower levels, i.e., constrains

FM 0: PD = [FM 1: Points scored for (PSF)] – [FM 2: Points scored against (PSA)]
FR 0: Control average point differential
DP 0: Fixed play calling strategy

FM 1: [FM 1: PSF] = [FM 1.1: Average expected point value (EPV)] * [FM 1.2: Number of possessions (NP)]
FR 1: Control PSF
DP 1: Fixed EPV maximizing strategy

FM 2: [FM 2: PSA] = [FM 2.1: Average opponent expected point value (OEPV)] * [FM 2.2: Number of opponent possessions (NOP)]
FR 2: Control PSA
DP 2: Fixed OEPV minimizing defensive play calling strategy

FM 1.1: [FM 1.1: EPV] = f (First downs, starting position)

FM 1.2: [FM 1.2: NP] = f (Interceptions caused, fumbles caused)

FM 2.1: [FM 2.1: OEPV] = f (First downs allowed, opponent starting position)

FM 2.2: [FM 2.2: NOP] = f (Interceptions givens, fumbles given)

Fig. 5: Top two levels of the 5 level fixed play calling strategy design solution and FM equations for the third level

them (Suh 1990).

Each FM's parent-child equation determines the next level of the decomposition (Henley 2015). Each lower level FM is a variable in the corresponding parent-child equation. FM 0 and its related parent-child equation are shown in Fig. 1.

PD depends on PSF and PSA. To control PD the user must control the two variables PSF and PSA. Thus there must be two FM-FR-DP sets at the next level, one to control PSF and the other to control PSA. As the solution for controlling the FM is not obvious, the FMs must then have their own children and parent-child equations to determine which lower FMs they are dependent on. This cycle is repeated until the solution for controlling the lowest level FMs is obvious. Sometimes the variables in the related equations are known but the exact formula for their combination is unknown. FM 1.2 is an example of that situation. Controlling the number of offensive possessions is a function of controlling the number of interceptions and fumbles in favor of the user's team. However, the exact form of the equation might not be known. The full decomposition, with the FMs, extends for five levels.

In the adapting design solution each FM has a time derivative to indicate when the design solution requires evolution.

If the derivative over time of any of the FMs stagnates or trends in an undesirable direction, changes to improve the standard work are made. If this does not solve the problem then a new DP is chosen.

2.2. Testing the solutions

An online, comprehensive, statistic-based game simulator called Action! PC Football (Koch 2016) was used to test the play calling strategies. This simulator mimics the performance of each team and their opponents from the selected season. The users call the plays and substitutes players. The statistics from the selected year are used to calculate results of each play called.

Three NFL teams were selected to represent the top, middle and bottom of the results from the actual season. The 2015 season was simulated for each of the selected teams, once with the fixed and once with the adaptive play calling strategy solution.

In both fixed and adaptive solutions the play calling choices are made to maximize the EPV of each series. EPV is FM 1.1, and is controlled by controlling the number of first downs and starting position of each series. Each play is chosen to consistently increase the EPV of that current series. Each position on the field has a specific EPV. On 1st, 2nd and 3rd down the play with the highest probability of forward progress is chosen in order to get the next first down, thus increasing the EPV of the series. During each 4th down, an equation is used to determine the EPV of three scenarios (1) going for the first down, or the touchdown if the goal line is closer than the distance required for a first down (2) punting (3) kicking a field goal. Whichever has the highest EPV is the choice made (Carter et al. 1971).

An example to illustrate making a decision using EPV would be 4th down at 5 yards to go on the opponent's 5 yard line. The user has two choices, kick a 3 point score or go for the touchdown. Based on Carter et al.'s (1971) data, the probability of a making a 3 point kick can range depending on the quality of kicker and the angle, but is about 75% on average. The probably of making a touchdown for 7 points is about 25% on average. The equation for EPV considers both the chance of the getting points combined with the EPV for succeeding minus the EPV from the resulting opponent's field position if the attempt to score fails. If the field goal is missed the opponent will begin their series on their 15 yard line (-0.64 EPV). If the touchdown fails, disbarring a turnover or loss of yards, the opponent will begin their possession somewhere between their 1 and 5 yard line (-1.3 EPV).

The equation for the field goal option (FGO) would be (1):

$$(1)\quad FGO\ EPV = \left(\left(0.75*3\right) - \left(-0.64\right)\right) = 2.89 \quad (1)$$

The equation for the touchdown option (TDO) would be (2):

$$(2)\quad TDO\ EPV = \left(\left(0.25*7\right) - \left(-1.3\right)\right) = 3.05 \quad (2)$$

So in this situation, using the design solutions in this work, the user would make the choice to go for the touchdown due to higher EPV.

Two changes were made to the settings for the simulations. All penalties were removed from simulations for the adaptive play calling strategy simulations. This is due to what seemed to be an uncharacteristically large number of penalties for fighting and other fouls for unsportsmanlike conduct. These are not related to the play calling, yet they can alter the result of a series, because they often grant an unearned first down. Also, the simulator features a limiter that forces injuries on a player if their yards gained on the simulated season will significantly exceed their actual totals. That limiter was switched off. This change does not prevent players from becoming injured as a part of the result of a play.

2.3. Comparing the two solutions: fixed and adaptive

The two design solutions have a few play calling differences.

With the initial, or fixed, design solution, the user chooses the offensive play that has the highest probability of success and a positive gain, factoring in what is needed to likely achieve the next first down. These gains are usually small, ranging between one and ten yards regularly, however they can consistently be relied on for a gain. The Action! PC Football simulator (Koch 2016) displays the probability of a positive gain with each possible play choice.

There are some situations where the user calls plays with a lower probability of successful completion on 2nd or 3rd down This is due to a negative result on a previous down. To get 10 yards over 3 plays, the user needs at least 3-4 yards on average each play. Sometimes a play can result in no gain or a loss of yards, requiring the user to gain over 10 yards in 1 or 2 plays to achieve a first down. The user must then consider choosing a play that has a lower probability of a successful completion but can result in a longer gain. This is because the plays with the highest probability of successful completion are unlikely to result in the larger gain needed for a first down.

The defensive play is always the same, based on the FM of minimizing the time the opposing quarterback has to deliver the ball. This depends on the number of pass rushers and when receivers get free from defenders. Therefore a minimum of 5 players rush at the quarterback every play. In conjunction, the pass defenders play tight man on man defense to limit the quarterback’s options.

At the start of the game, the adaptive design solution uses the offensive play calling strategy of the fixed design solution. The derivative over time for each FM is monitored and changes are made if the values of the current FMs trend in an undesired direction. Similar to Cochran et al. (2016) attempts to improve the standard work are made, and, if unsuccessful, a different DP can be chosen. Offensively, this DP might be the type of play being called. Similarly on defense, the number of players rushing the quarterback, the number of players in pass defense and the scheme can change as they are the DP for controlling their related FM.

Sixteen games, a full season, are played on the Action! PC Football simulator (Koch 2016) using these strategies. The value of each FM is recorded at the end of every game and totaled for the season. The means and standard deviations for the top two levels of FMs are calculated for both design solutions and compared to those from the actual season.

3. Results

For each simulation the mean and standard deviation for points scored, opponent points and PD have been collected. The results of each design solution are compared to each other and to the actual season. Fig. 2 is an example of the compared means and standard deviations for PD. In this case, the

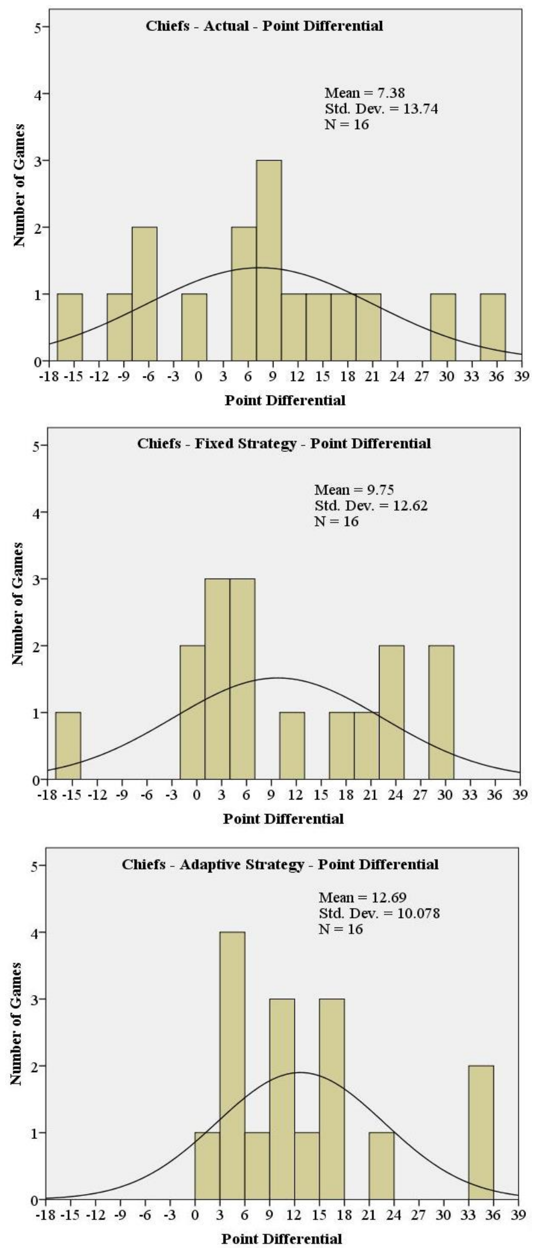

Figure 6: Chiefs' means and standard deviations histograms

figure shows comparisons in PD while using the Kansas City Chiefs. This specific data set was illustrated as it best represents the expected improvement when applying the design solutions. There is noticeable improvement in PD with the design solutions compared to 2015 play calling strategies, PDs of 9.75 and 12.69 for fixed and adaptive compared to 7.38 for actual. Similar results for lower level FMs can be found in Henley (2016).

The means and standard deviations for PDs for the all three teams for the actual season and the fixed and adaptive design solution strategies are compared in Tables 1 and 2.

Table 1 shows the means for the FMs of the design solution's top two levels. The mean for points scored and PD for each team was higher with the design solutions' play calling than during the actual 2015 season (Henley 2016).

The adaptive play calling design solution does not always do better than the fixed play calling strategy. The mean PD was lower for the Seahawks using the adaptive strategy.

The opponents points scored did not always go down with the design solutions compared to the actual season.

The standard deviations for points scored, opponent points and PD were smaller with the design

Means:	**Actual**	**Fixed**	**Adaptive**
Seahawks			
Points scored	26.44	36.13	31.00
Opponent points	-17.31	-15.50	-21.25
PD	**9.13**	**20.63**	**9.75**
Chiefs			
Points scored	25.31	31.63	33.00
Opponent points	-17.94	-21.88	-20.31
PD	**7.38**	**9.75**	**12.69**
Browns			
Points scored	17.38	25.19	26.94
Opponent points	-27.00	-29.56	-23.63
PD	**-9.63**	**-4.38**	**3.31**

Table 1: Means for the regular season's 16 games

solutions' play calling than during the actual 2015 season (Table 2). There is an increase in the standard deviations for opponent points scored in the fixed solution compared to the actual season.

The standard deviation of the adaptive strategy could be somewhat misleading (Table 2). Excluding what could be two outliers with PDs was in the 33-36 range, positive results that exceed expectation, the standard deviation was 6.

Table 3 shows the actual, fixed and adaptive strategies win-loss records of the teams. The record for each team was better with the design solutions than the actual 2015 results. The adaptive play calling design solutions results in the best win-loss records overall.

The adaptive play calling design solution in particular offers the greatest advantage when comparing the three top level FMs included in this work. The play calling strategies designed by AD achieve better records than the actual 2015 season's play calling strategies.

Standard deviations:	**Actual**	**Fixed**	**Adaptive**
Seahawks			
Points scored	8.39	9.12	7.63
Opponent points	11.75	8.30	7.92
PD	***14.12***	***11.59***	***9.44***
Chiefs			
Points scored	8.95	8.85	6.79
Opponent points	9.77	10.07	5.37
PD	***13.30***	***12.22***	***9.76***
Browns			
Points scored	8.71	7.67	8.66
Opponent points	7.17	10.55	6.25
PD	***12.7***	***10.89***	***10.1***

Table 2: Standard deviations for the regular season's 16 games

Win-loss records:	**Actual**	**Fixed**	**Adaptive**
Seahawks	10-6	16-0	15-1
Chiefs	11-5	13-3	16-0
Browns	3-13	6-10	11-5

Table 3: Win-loss records for the regular season's 16 games

4. Discussion

This design process could be applicable in other sports and situations requiring winning strategies. Also, AD is more than the decomposition and metrics, which have been emphasized here. It is about compliance with the independence and information axioms. Independence is maintained (axiom one) during the decomposition in part by being CEME and the FMs help to accomplish that. In addition, minimizing information (axiom two) can be re-stated as maximizing the probability of success in fulfilling the FRs. The attention to the probability of success used here in selecting the plays, e.g., the EPV, works to comply with axiom one.

The results indicate that the design solutions in this work are superior to actual play calling in 2015. However, these results cannot be considered the same as actual games. Using a simulator, the user is able to bypass possible obstacles like player and team staff buy-in to what might be considered a radical play calling approach. The simulator also allows the use of players far beyond the point that the coaching staff would have removed them for fear of injury.

4.1. Mean PDs

The mean for points scored for each team was higher in the design solution's data than during 2015. The PD was also higher in the design solutions than during 2015. This might indicate that the design solutions feature a more effective offensive play calling strategy than was used in 2015. The histograms for PD in Fig. 2 for the adaptive strategy show particular improvement to 12.69 in part because there are no instances of negative PD due to an undefeated season.

There could are three reasons why the opponent's average points scored increased overall. The first is a choice to prioritize certain FMs that give the opponent higher yards gained per play but favors turnovers, compared to the actual 2015 season. The second is because as the users increase their number of scoring possessions, the opponent will have more possessions. The opponent's average points scored might increase but the users' increase more. The third reason is that at the end of the game when one team is almost guaranteed victory, different choices are often made. The defensive play scheme moves to prevent long gains and quick scores and allows the opponent to make short gains more easily. This runs out the playing time, limiting the chances for the opponent to catch the score the users.

The win-loss records are one possible result of a high positive point differential. Even though there are some undefeated seasons, the same point differential over the entire season could occur with a worse win-loss record. A higher positive point differential increases the chances of but does not guarantee wins.

4.2. Variation of the PDs

The standard deviations for points scored, opponent points and PD were smaller for the design solutions than during the 2015 season. This shows that not only are the users outperforming the opponent but the users have greater control over how much they outscore the opponent by.

One surprising result is how low the standard deviation is for the opponent's points scored. This shows that the design solutions outperform the actual 2015 play calling strategies. This is possibly more important than an improvement in the means for each stat. Improved certainty (reduced standard deviation) is an important result when designing solutions with AD because it reduces the information content (axiom two). A good design solution offers the user better control, i.e., less uncertainty.

The results for the simulated season for the Seahawks using the adaptive play calling strategy, with the one loss, might be an outlier. The two starting running backs and four of the five starting offensive linemen were injured most of the season, as was the highest scoring receiver from the fixed strategy simulation. This is not something that commonly occurs in a single season. This reduced the probability of positive gains on every play and inhibited the ability of the team to score points consistently. As a result, the opponent had the ball more often than they normally would have and therefore scored more points.

4.3. Metrics

Every simulated season had the user's team in last place in the league in every passing statistic except the completion percentage, in which each team was in the top five. Yet even so, each simulated team surpassed the PD of the team during the actual 2015 season. Many consider these passing statistics important.

This might suggest the current allocation of salary, within the league-imposed cap, by position can be improved. The increased use of running backs led to many injuries on the offensive line and to the running backs during the simulations. Teams might be better prepared to outscore their opponents with more money spent on the offensive line and running backs and less on the quarterback.

5. Conclusions

Several things can be concluded from this work: First, axiomatic design (AD) can be used advantageously to design game-winning strategies in American football. Second, AD with functional metrics (FMs) and their related parent-child equations facilitate top-down decompositions for the design of play calling strategies, which provide for scoring points and preventing the opponent from scoring points and clearly have applications in other competitive situations in games and business. Third, the key metrics resulting from the application of AD with FMs for evaluating performance details are different than many of the metrics commonly thought to be important in American football, e.g., passing yards. Fourth, play calling strategies created with AD using FMs, for both fixed and adaptive design solutions, appear to be better for winning games than the actual play calling used in the NFL.

Future work should test extending this approach, using functional metrics rigorously to other games and competitive situations. FMs and adaptive designs should be developed so that they can be applied systematically to a broad range of situations.

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Appendix A. Scoring and ball control in American football

Six points are scored when one team brings the ball across the opponent's goal line into the opponent's end zone, and then a seventh point can be scored by kicking a "point after".

The playing field between the end zones is one hundred yards long. At the beginning of each half and after each score the play starts with one team kicking off to the other. The other team can run it back until they are stopped and the ball is "downed", marking the position on the field for the start of the next play.

Offensive plays can involve combinations of running, when the ball is carried, or passing, when the ball is thrown. There are precisely defined roles and routes for each player which are play dependent. Each play continues until the ball carrier is tackled to the ground or forced out of bounds, which downs the ball.

If the offensive team has not progressed at least ten yards in four plays, or downs, then they must turn the ball over to the opponent. Therefore, on the fourth down the offensive team often decides to "punt", i.e., kick the ball down the field, thereby giving the opponent a less advantageous starting position for their series of plays. The other options are to "go for it" to see if they can manage the rest of the ten yards on the fourth play, or to try for a field goal, i.e., kicking the ball between goal posts, for three points.

If the offensive team has progressed at least ten yards in four downs, i.e. with four plays, or fewer, then they are awarded a "first down" and start again trying to get another ten yards in four downs or score.

The defensive team also has plays that often attempt to anticipate a pass or run type offensive play.

The offensive team can lose the ball as described above on downs or a punt or due to a "turnover", where a runner drops the ball in a "fumble" that is recovered by the defensive team, or where the defensive team intercepts a pass. Play then continues until the ball is downed or the defensive team scores a touchdown. The defensive can also score 2 points with a "safety" where they tackle the ball carrier in the offensive teams own end zone.

Before each play the players and coaches can consult to decide which play to run. To begin each play, the offensive and defensive players line up on either side of the ball, where it was previously downed. Once they see each other's line up they can call "audibles" to change their plays. The play starts when the "center", an offensive player who lines up on the ball, "hikes" the ball to the "quarterback".

The moment the center moves the ball the players can cross the line where the ball was placed separating the two teams. The quarterback then can hand the ball off to a running back for a running play, or pass the ball to a receiver for a passing play. The quarterback can have several receivers to pass to, depending on the defensive coverage. Defensive players can rush the quarterback, guard against a run or cover potential receivers to guard against a pass.

Chapter 4: Examining how functional metrics can be used to simplify the decomposition process within axiomatic design

1. Introduction

1.1 Problem Statement

The objective of this work is to examine how functional metrics (FMs) and their related parent-child equations can be used to facilitate and simplify the decomposition process within axiomatic design (AD) compared to a qualitative approach.

A functional metric (FM) indicates how well a FR satisfies a customer need (CN). Simplifying is defined as making something more easily understood.

The scope of this work is in applying FMs to control the return on investment (ROI) of a small manufacturing enterprise (SME). Specifically, FMs are applied to controlling ROI by controlling the production processes of a SME.

The AD framework provides a process for developing design solutions with a high probability of success. The optimal solution is often referred to as one that is collectively exhaustive mutually exclusive (CEME). CEME means that the children of all the functional requirement, design parameter (FR DP) pairs are collectively exhaustive with respect to the parent and mutually exclusive with respect to each other.

In an attempt to arrive at a CEME design solution, a designer collects CNs, which are used to determine which functions must be controlled to add value to the customer. Control is defined as obtaining a desired system response (output) based on a specific stimulus (input) (Dorf and Bishop 2001). A zig-zag decomposition process between the functional and physical domain is used in an attempt to ensure a collectively exhaustive solution. The design matrix is then used to determine which if any of the functions being controlled are coupled with each other ensuring mutually exclusivity.

However, a zig zag decomposition process and filling in the design matrix might be difficult and cumbersome for some users. This could be especially true for newer students of AD who might have less experience with developing CEME design solutions. This possible issue of determining CEME could be decomposed into two child issues:

(1) How can a designer be sure that they have thought of every function that should be included and that no functions have been included in excess?

(2) How can the designer be sure that the functions being controlled do not inadvertently affect each other?

To address the first child issue, use of a qualitative theme has been suggested to facilitate developing a CEME design solution. This can be helpful for fleshing out possible parts of a design solution that the designer might not have considered and included otherwise. However, as it is a qualitative approach, there is no objective justification for CEME.

To address the second child issue, AD uses a design matrix to record instances of coupling within a design solution. During instances of partial coupling, the design matrix serves as a tool to determine an order of operations to achieve a triangular matrix. In a partially coupled solution, the triangular matrix alignment allows the user to adjust the solution to achieve the desired results in one iteration without having to re-adjust a previously adjusted function. However, without a quantitative method for determining coupling, filling in the design matrix relies on judgment calls from the user.

These two child issues can be even more difficult to resolve once an initial design solution has been developed or when a design solution must evolve to remain valuable, and as a result, a customer expresses more CNs. There are times when a customer thinks of new CNs in a later discussion that they consider relevant to a CEME design solution. This can be done without the customer expressing the importance of the new CNs relative to the older CNs or where in the design solution the new CNs should be included. Cochran (2013) acknowledges this problem which he labels "requirements soup." This can also be an issue in an evolving industry. Over time, it is possible for there to be new functions that must be controlled in order for a SME to remain competitive. The design solution must be able to reliably evolve to remain valuable to the user. In this case, it could be helpful to have a tool that facilitates determining where the new functions should be included in the evolved design solution.

When applied to a SME, a lack of quantitative method for determining CEME and coupling could make it difficult for decision makers to see the value that AD can have toward controlling their ROI.

1.2 Rationale

FMs and their parent-child equations can be valuable in multiple ways within axiomatic design. A CEME design solution can improve controllability compared to a non-CEME design solution. The design solution provides value to the user based on:

(1) How effectively controlling the lower level functions increases the output of the top level function

(2) How similar the actual output is compared to the desired output

Control can be reduced by including functions in the design solution that do not affect the top level FM or by leaving out functions that do affect the top level FM. FMs and their related parent-child equations show which functions need to be controlled for a CEME design solution and which should not be included.

Undesired output variety due to coupling can result in a loss of value to the customer or increase costs. The likelihood of a loss of value due to the output being out of tolerance increases as the variety of the output increases. Another source of lost value can come from non-value added iterations in an attempt to get the output back within tolerance. Using parent-child equations at every level identifies coupling and can prevent a loss of value.

Currently, the design matrix is used to determine and record coupling. The process can be time consuming and inaccurate, sometimes relying on the user to make judgment calls. FMs and the variables within their related parent-child equations provide quantifiable evidence for determining if any coupling exists. If any parent-child equations share a common variable, coupling must be present and can be quickly identified. If no parent-child equations share a common variable, the design matrix step can be skipped and time saved.

Having FMs in a design solution can facilitate translating CNs into the subsequent domains. Traditionally, collecting a list of CNs is one of the first steps in the axiomatic design process. CNs are then used as constraints or mapped from the customer domain into the functional and physical domain until every CN is accounted for. However, this assumes that all expressed CNs should be present in a CEME design solution. The customer might be express CNs that have no effect on the top level FM. Beginning with a top level FM and decomposing using parent-child equations can facilitate determining which expressed CNs are relevant to controlling the top level FM.

There can be times when internal or external factors cause certain functions within the design solution to no longer be as valuable to the user. In response, the design solution must evolve to remain valuable to the user. During the review process to evolve the design solution it might be difficult to determine which functions need to be removed and where new functions might fit within the design solution. It might also be difficult to determine which candidate DPs for new functions might cause coupling with other parts of the design solution. FMs and their related parent-child equations can facilitate identifying where new functions might fit within the design solution and whether or not coupling exists due to repeated variables in multiple parent-child equations.

A simpler decomposition process could prevent users from abandoning AD due to difficulty. There might be potential users of AD or customers interested in a potential design solution developed through AD that abandon AD due to the potentially cumbersome nature of using the decomposition process and the design matrix. Harvey (2010) writes, “in the face of complexity, we just shut down. What we don’t understand, we ignore. What we ignore, we are bored by and move past.” Using FMs and their related parent-child equations can facilitate the decomposition process and determine coupling. This could both simplify the decomposition process and reduce the need for the design matrix, which some users might consider two difficult parts of using AD.

1.3 State of the Art

There has been previous work done on maintaining CEME and its importance within an effective design solution. Dickinson and Brown (2009) write that a good hierarchical decomposition must be CEME min, which means using the minimum number of FRs while remaining collectively exhaustive and mutually exclusive. Originally, this was known as MECE, “mutually exclusive, collectively exhaustive.” MECE was a method for reducing the parts of a system to non-overlapping modules to make sure no part of the system has been unaccounted for (Rasiel 1999). MECE then became CEME, with the belief that the first step is to make sure everything has been thought of followed by ensuring independence of the functions to increase control.

Henley (2015) writes about the effectiveness of developing FMs before FR DP pairs. A top level FM should be developed and then decomposed by defining a related parent-child equation containing variables that combine to equal the FM. FRs should be a restating of the FM, “control [FM X].” DPs should determine the scope of what is being controlled in the related parent-child equation. At the next level of the decomposition, the number of FMs and therefore FR DP pairs should be equal to the number of variables in the parent equation, each variable being controlled independently.

Suh (1990) describes a method for a hierarchical zig-zag decomposition process. The user alternates between asking "what" and "how" by determining what a function should accomplish and how to satisfy a function with a physical solution. A DP is developed to limit the scope of the next level of FRs. Suh (1990) also writes of the design matrix being used to facilitate the management of coupling within a design solution. Any coupled elements are non-zero terms in the matrix. The optimal solution is one in which there is no coupling. In the case of an optimal solution, the matrix is diagonal, meaning the only non-zero terms are in a diagonal line down the matrix. This way, functions within the design solution can be fulfilled in any order to get the desired output. A less favorable but manageable solution is a partially coupled solution. In this case, the matrix can be sorted to be triangular. This means that the only non-zero terms will be on one side of the diagonal non-zero line. In this case, functions cannot be carried out in any order but an order of operations can be determined to get the desired output in a single iteration.

FMs have previously been used in axiomatic design. Suh (1990) gives many examples of decompositions with metrics for both FRs and DPs. The commonly used water faucet example features a vertical motion to control flow, which is assigned the FM "Q" and a horizontal rotation to control temperature, which is assigned the FM "T."

In the context of ROI, Suh (2001) proposed that ROI can be decomposed to three main FRs:

(1) Increase sales revenue

(2) Minimize cost

(3) Minimize investment

He decomposes a FM and a related parent-child equation for FR 0, ROI = (Sales - Cost / Investment), though without the "FM" or "parent-child equation" terminology. The next level of FRs and DPs are used to control each variable in the parent equation independently.

Manufacturing System Design Decomposition (MSDD) (Cochran 2002) was similarly designed using the same top two levels of FRs that Suh (2001) used to satisfy the goal of maximizing return on investment. MSDD is decomposed down the lowest level of functions that might be controlled by a SME and relates them to the top level function being controlled, "maximize ROI."

There has been work done on the need for regular evolution within design solutions, which are often referred to in the literature as performance measurement systems. Kaplan and Norton (1992) write that a design solution can evolve over time through regular review and adjustment of the metrics to ensure that the design solution continues to be valuable. This kind of evolving design solution can save an organization the expense of having to develop a new design solution.

The performance paradox model (Meyer and Gupta 1994) explains the inevitable need for evolution as a requirement in every design solution to avoid obsoletion. A new set of metrics will need to be defined that measure the same value to the user as the success rate of current design solution becomes stagnant or trends in an undesired direction.

Farrell (1985) writes about the use of standardization to reduce output variety and increase the value of a design solution. He warns of the trap that standardization without sufficient information can cause, leading a SME to stick to obsolete practices when a more valuable alternative is available.

Collective System Design (CSD) is a method for developing design solutions based on AD (Cochran et al. 2016). CSD provides a behavior and process for collective agreement during a SME's conversion to lean manufacturing, to achieve long term sustainability. This includes assigning metrics to FRs and DPs where needed. According to Cochran et al. (2016) there are three options when the performance of FMs and related FRs are no longer acceptable:

(1) Improve the standard work without choosing a new DP

(2) Choose a new DP

(3) Choose a new FM and FR.

1.4 Approach

Two iterations of a design solution have been developed for controlling ROI during the production processes within a SME. The first does not feature FMs and the second features FMs at every level. The possible benefits of using FMs at every level to simplify the decomposition process and avoid the need for the design matrix are examined. The SME is considered the customer and the user of the design solution.

Similar to Dickinson and Brown (2009), the two design solutions in this work are developed while attempting to maintain CEME. Unlike their work, the second design solution in this work uses FMs and related parent-child equations to provide a quantitative method for developing CEME design solutions versus a qualitative theme.

Similar to Henley (2015), parent FMs appear as dependent variables which rely on mathematical equations or formulas containing other variables. These FMs decompose into children FMs. The children FMs are each variable from the parent equation or formula. The decomposition process continues down to lowest level of independent variables. FR DP pairs are designed to control each FM independently. This process of decomposing using FMs and their related parent-child equations serves as quantitative justification for CEME.

Unlike Suh (1990), CNs are not mapped to FRs and DPs. A FM 0 is developed and decomposed. CNs are used as constraints when developing relevant DPs. A process similar to zig-zag decomposition is done between the FM and the DP. The DP defines the scope of the next level of the decomposition and therefore can affect which variables are present in the FM equation.

Similar to Suh (2001) and Cochran (2002), the second design solution in this work uses an equation similar to their ROI equation for the top level FM. Unlike their work, potential ROI is used instead of ROI. Unlike Cochran (2002), this work features a more simple decomposition with the same goal.

Similar to Kaplan and Norton (1992) and Meyer and Gupta (1984) the second design solution in this work will go through review and evolution to ensure long term value to the user. Unlike their work, it will not be during regular intervals. A derivative over time is continuously monitored for each FM to determine when the design solution needs to be evolved.

Similar to Farrell (1985) standardization is used within the design solutions in this work to add value to the user and reduce output variety.

Similar to Cochran (2016), the same steps used to adjust an underperforming design solution, improve the standard work, choose a new DP, and then lastly choose a new FM FR pair.

2. Methods

Two distinct iterations of a design solution have been developed for controlling ROI during the production process phase within a SME. The first iteration is a design solution developed before the use of FMs. The second iteration is a design solution developed using FMs and their related parent-child equations at every level.

2.1 Iteration without FMs

The first iteration of the design solution was developed before the use of FMs had been considered. This iteration was developed using the more common FR DP zig zag decomposition process. CNs were collected from the customer. Each CN was mapped to a FR, DP, or determined to be a constraint. CNs were collected over multiple meetings with a SME. Development of this first iteration began after the first meeting with the SME and was then altered as new CNs were expressed. This iteration cannot be considered CEME. There were several difficulties that prevented the development of a CEME design solution.

Figure 1 is the final list of CNs after multiple meetings with the customer. These CNs were collected with no expressed priority on one CN versus another. Certain CNs in this list seem to be expressed as constraints on candidate DPs. An example of this is:

CN 17: Visual interface for data

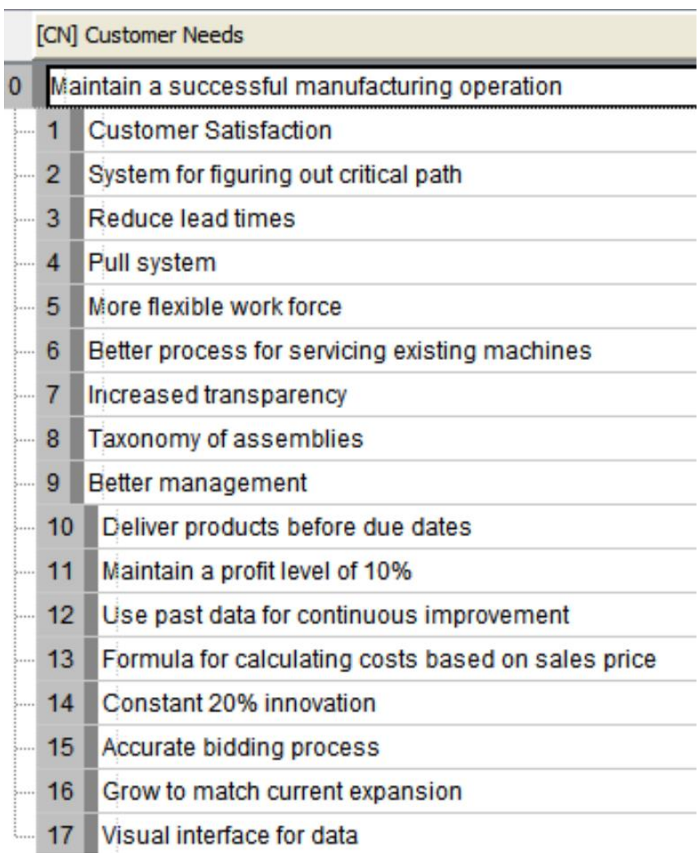

Figure 7: Final list of CNs

Others seem to be expressed as desired FRs by the customer. An example of this is:

CN 12: Use past data for continuous improvement

These CNs are all meant to be a child of the top level CN:

CN 0: Maintain a successful manufacturing operation

However, there is no quantitative way to justify that the list of CNs is CEME or determine which CNs might be children of other CNs.

There was difficulty in mapping CNs to FRs, DPs, and constraints. When the current list of CNs from each meeting had been mapped to the functional and physical domains, the result was a decomposition that never seemed to be collectively exhaustive. Figure 2 is the furthest the first iteration ever got to being CEME design solution.

The top level FR is:

FR 0: Create a sustainable manufacturing company

It was determined that FR 0 was a combination of two functions:

(1) Create consistent business by providing a high level of customer satisfaction (FR 1)
(2) Control the profit from the consistent business (FR 2)

Similar to Cochran's (2002) MSDD, increasing customer satisfaction is the design parameter for increasing income. The logic used when design this first iteration was that a SME cannot increase the revenue from any specific order higher than what the customer has agreed to pay and therefore cannot increase profit past a point. However, they can control how well they handle an order and therefore satisfy a customer. A satisfied customer would be likely to bring business to the SME regularly. The result would be a consistent stream of profit.

Similar to Cochran's (2002) MSDD, "increase customer satisfaction" (FR 1) was decided to be a combination of three functions:

(1) Meet the customer specifications with minimal variation in the output (provide consistent quality) (FR1.1)

(2) Give the output to the customer by the agreed upon date (provide on time delivery) (FR1.2)

(3) Make that date as soon as possible (reduce lead time) (FR 1.3)

CNs were mapped to logical positions within the design solution in an attempt to provide value to the customer. Certain CNs did not fit as children, siblings or parents to any other FRs or DPs in the decomposition and could not logically be labeled constraints. Therefore, they had to be left out. Almost half of the FRs, all of which were required as children FRs to be logical CEME decompositions of their parent FRs, were without related CNs. Even when most of the CNs were mapped to the other domains in the decomposition, the customer was not convinced that the design solution would satisfy CN 0. New CNs were expressed at later times in an attempt to make the design solution more valuable to their production process needs. No version of this first iteration satisfied the customer. No version of this iteration was able to feature every CN and remain a logical decomposition.

There was difficulty achieving a CEME version of this first iteration. It was obvious that the design solution was not CEME with respect to the expressed CNs due to unused CNs. There was no quantitative way to determine whether some unused CNs should be mapped to the other domains within the design solution. Furthermore, there was no quantitative way to tell if some CNs mapped to the other domains within the design solution were unnecessary.

#	[FR] Functional Requirements	[DP] Design Parameters	[CN] Customer Needs
0	Create a sustainable manufacturing company	0: System for creating a systainable manufaturing	0: Maintain a successful manufacturing operation
1	Increase customer satisfaction	1: Short term processes	1: Customer Satisfaction
1.1	Provide a high quality product consistently	1.1:	
1.1.1	Consistently meet target product specifications	1.1.1:	
1.1.1.1	Standardize designs products that have been created before	1.1.1.1:	8: Taxonomy of assemblies
1.1.1.2	Train workers to be able to mimic standard work methods	1.1.1.2:	
1.1.2	Innovate to anticipate future customer needs	1.1.2:	14: Constant 20% innovation
1.1.3	Develop a machine servicing plan that eliminates downtime	1.1.3: Machine servicing system	6: Better process for servicing existing machines
1.1.3.1	Design products for easy part removal	1.1.3.1:	
1.1.3.2	Service parts regularly instead of when they break	1.1.3.2:	
1.2	Deliver products to the customer as early as possible	1.2:	10: Deliver products before due dates
1.2.1	Reduce disruptions	1.2.1:	
1.2.1.1	Reduce worker based disruptions	1.2.1.1:	
1.2.1.2	Reduce process based disruptions	1.2.1.2:	
1.2.2	Plan in slack time in case of disruptions	1.2.2:	
1.2.3	Identify critcal paths in designs	1.2.3:	2: System for figuring out critical path
1.2.4	Prioritize work in the critical path to be started as soon as possible	1.2.4:	
1.3	Reduce the lead time on projects	1.3:	3: Reduce lead times
1.3.1	Avoid non productive iterations in design	1.3.1: Assembly design based on axiomatic design	
1.3.2	Remove time spent on base assemblies common in most designs	1.3.2:	
1.3.3	Identify areas of expertise to best use experience	1.3.3: Assignment by speciality	
1.3.4	Review processes over regular intervals to search for improvement	1.3.4: Ongoing data comparisons to the past	12: Use past data for continuous improvement
2	Maintain a profit level of 10%	2: Continuous Improvement system	11: Maintain a profit level of 10%
2.1	Increase revenue	2.1:	
2.1.1	Make reasonable profitable bids	2.1.1: Successful bidding stragegy	15: Accurate bidding process
2.1.2	Grow the business through new clients	2.1.2: New customer system	16: Grow to match current expansion
2.2	Control costs	2.2:	
2.2.1	Procure materials at lowest cost without compromising quality	2.2.1: Material procurement process	
2.2.2	Monitor current productivity level	2.2.2: High productivity practices	7: Increased transparency
2.2.3	Assess data on current progress continuously	2.2.3:	12: Use past data for continuous improvement

Figure 8: Iteration developed before the use of FMs

This first iteration suffered from the “requirements soup” problem that Cochran (2013) wrote about. The meetings that followed the first resulted in a plethora of new CNs, some of which did not seem to have a place in the current design solution. Furthermore, the new CNs were expressed without any explanation of their priority or position relative to previously expressed CNs.

There was difficulty determining coupling in this iteration. With the aforementioned difficulty with the decomposition process, it was difficult to determine whether certain FR DP pairs were correctly related. For example, two sibling FR DP pairs would seem like they might have also shared a parent-child relation. Due to the innately coupled nature of a parent FR DP pair to its child, it was difficult to determine if sibling coupling was the result of incorrect positioning of an FR DP pair in the decomposition. Furthermore, it was difficult to determine if FR DP pairs that should be siblings were coupled. With no FMs to relate any FR DP pairs to each other, there was no quantitative way to determine whether adjusting one FR DP pair would affect another.

2.2 Iteration with FMs

A second iteration of the design solution was developed using FMs in the decomposition process (Figure 3). The top level FM was:

FM 0: Potential return on investment (PROI)

PROI was determined to be the top level FM by asking the customer what they would measure over time as the main metric of whether or not the design solution was satisfying CN 0. The FR column is

	[DP] Design Parameters	[FM] Functional Metrics
0	Production process that prioritize long term ROI	PROI = (Potential revenue (PR) - cost) / investment
1	Production processes that consistently provide customer satisfaction	PR = Revenue [SBC] * ((On time % (OTP)) / (1 - variation (V))
1.1	Production processes that consistently provide expected output	V = Design variation (DV) + production variation (PV)
1.2	Production processes with minimal disruption	OTP = Expected completion time (ECT) [SBC] / (ECT [SBC] + (Response time (DRT) * # disruptions (ND)))
1.2.1	Rapid disruption reaction system	DRT = Time to recognize + time to contact problem resolvers (TTC) + time to resolve (TTR)
1.2.1.1	Measurement of output after each step in production	DRD
1.2.1.2	Defined easy to access communication paths to problem resolvers	TTC
1.2.1.3	Standardized methods for resolving each disruption cause	TTR
1.2.2	Disruption root cause elimination system	ND = Worker disruptions (WD) + Machine disruptions (MD) + raw material disruptions (RD)
2	Production processes that reduce non-value added sources of cost	Cost = Direct waste (DW) + indirect waste (IW)
2.1	Reduction of non-value added manual tasks	DW = Worker waste (WW) + Machine waste (MW)
2.2	Reduction of non-value added tasks related to support systems	IW = Managerial waste (MW) + informational waste (NW)
3	Production processes that control investment to ensure long term survivability	Investment = Material investment + lead time

Figure 9: Iteration developed with FMs at every level

not displayed because each FR is the related FM restated, for example:

FM 1: Potential revenue

FR 1: Control potential revenue

Once the top level FM, PROI, was determined, this was the starting point of the decomposition (Figure 4). CNs were not mapped to FRs or DPs and instead served to constrain candidate DPs. A FR DP pair was developed to control FM 0. The customer had expressed that the scope of the design solution was to be the production processes of the SME. As a result, the scope of DP 0 was the production processes of the SME:

FM 0: Potential ROI

FR 0: Control potential ROI

DP 0: Production processes that prioritize long term ROI

With no other information, the method for determining the value of PROI is not obvious. As a result, FM 0 must have an equation or formula of variables that combine to equal FM 0 (Figure 5). There are three variables present in the parent-child equation:

(1) Potential revenue

(2) Cost

(3) Investment

As a result, there are three direct children of FM 0, equal to the number of variables in the parent-

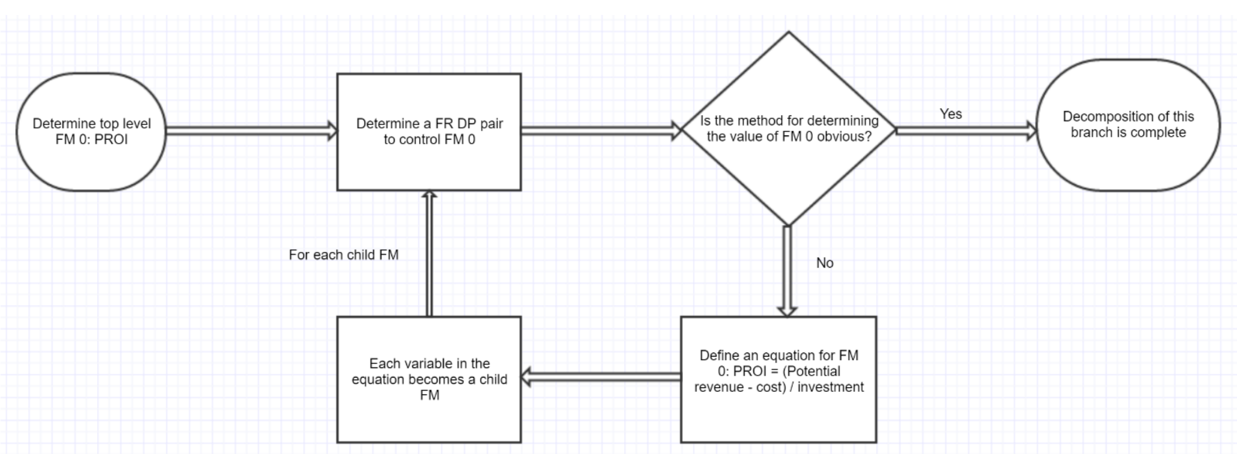

Figure 10: Flowchart for decomposing with FMs

child equation. Each of the direct children FMs are one of the variables from the parent-child equation in the level above. This process repeats for each of the variables in the parent-child equations (Figure 4).

The chosen DP constrains the scope of the variables in the related parent-child equation and all lower levels of the decomposition to functions that affect the production processes. Unit FR FM DP 2 is an example of this:

FM 2: Cost

FR 2: Control cost

DP 2: production processes that reduce non-value added sources of cost

Cost can be the combination of many different smaller costs. The scope of the costs to be controlled in this situation are non-value added sources of cost as defined by DP 2. As a result, the variables in the related parent-child equation are “direct waste” and “indirect waste” and none of the value added costs are included.

There is an exception to having a child FM for each variable in a parent-child equation (Figure 6). The parent-child equation features three total variables:

(1) Revenue

(2) On time %

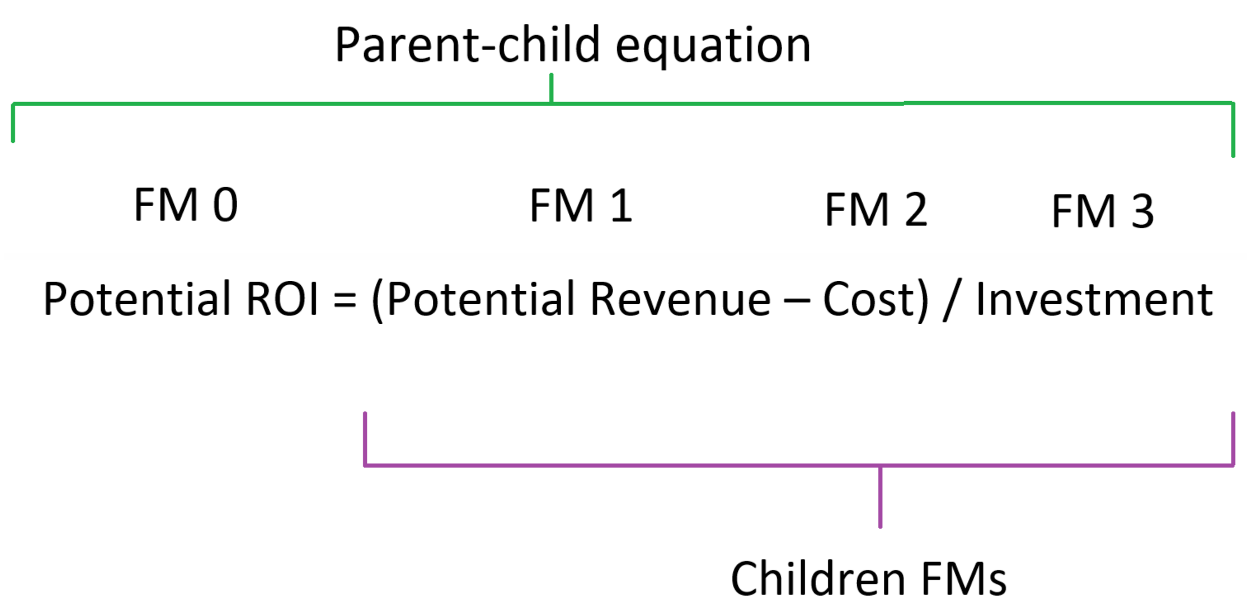

Figure 11: FM 0 and its 3 children FMs

(3) Variation

Revenue must be a variable in the equation for determining potential revenue. However, revenue is "SBC", which means supplied by the customer. Revenue is not being controlled within the design solution. As a result, there are two children FMs, "on time %" and "variation," the two variables being controlled within the design solution.

The decomposition process using FMs and their related parent-child equations is continued until developing a FM that is no longer the combination of other variables or the method for acquiring the value of the FM is obvious. An example of this is:

FM 1.2.1.1: Disruption recognition delay time

FM 1.2.1.2: Time to contact problem resolvers

FM 1.2.1.3: Time to resolve the problem

These three FMs are not the combination of any other variables and are instead just measurements of time. The method of measuring the value of these FMs is obvious. Therefore, this is the lowest level of that branch in the decomposition.

FMs and their related parent-child equations can reduce the time spent developing a design matrix. Each parent-child equation is made up of variables that combine to equal the FM and relate lower

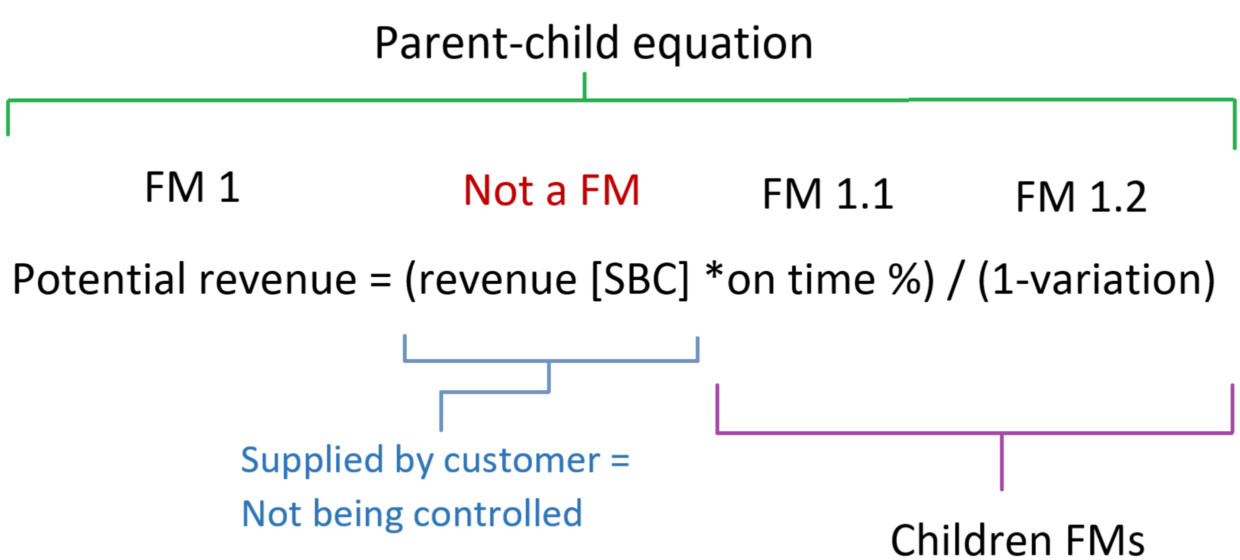

Figure 12: FM 1, its 2 children FMs and a metric being supplied by the customer

level functions to higher level functions.

Figure 7 is an example of how FMs can reduce time spent developing a design matrix. As stated previously, the DP determines the scope of the variables in a parent-child equation. In this case, DP 2 limits the scope of the variables affecting cost to those that are non-value added sources of cost. DP 3 limits the scope of the variables in its parent-child equation to costs that are investments made to control customer satisfaction and therefore control potential revenue. None of the variables in FM 2's parent-child equation are the same as those in FM3's parent-child equation. Therefore, the user has quantitative justification for concluding that there is no coupling in the design solution up to this point. In a design solution where all of the FMs are similar to this situation, meaning no parent-child equations have repeated variables, there is quantitative justification for concluding that there is no coupling within the design solution. As a result, the user can avoid spending time developing in the design matrix.

Figure 8 is an example of repeated variables within multiple parent-child equations. A different DP for DP 2 has been chosen in this situation compared to Figure 7. In this situation, DP 2 includes all sources of costs instead of just non-value added sources of cost. As a result, the variables in the parent-child equation change to the new scope determined by the altered DP 2. DP 3 has remained the same as the DP 3 in Figure 7. Looking at the parent-child equations for FM 2 and FM 3, there is a repeated

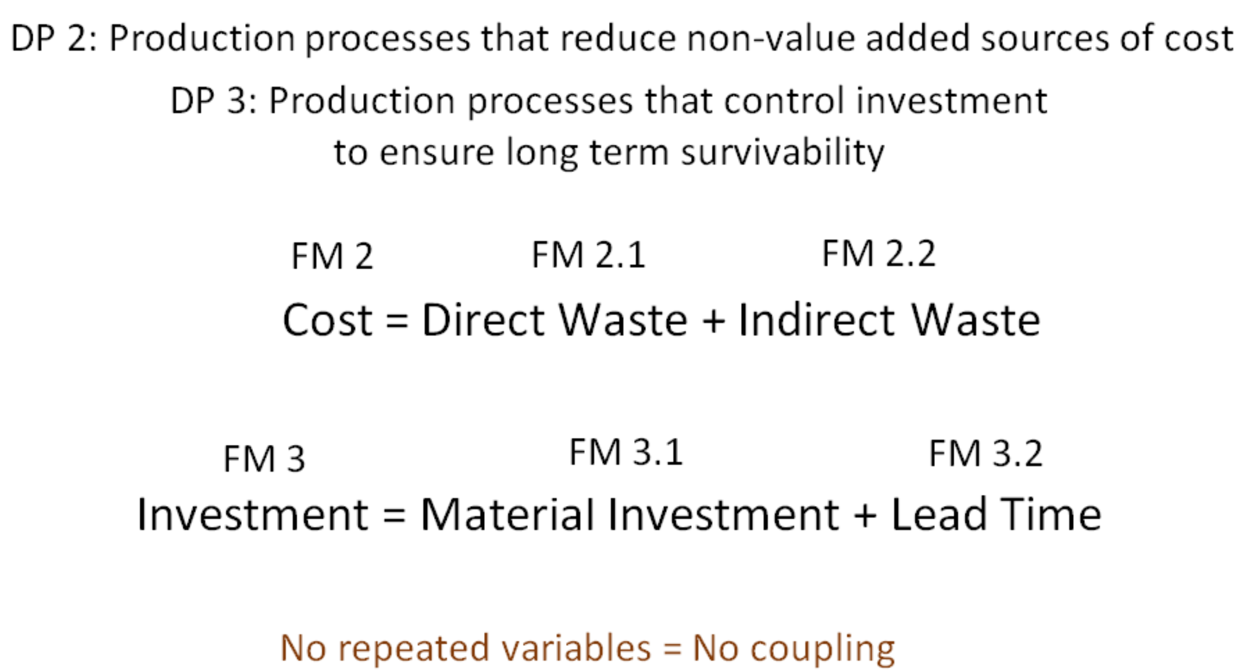

Figure 13: Two FMs and their related parent-child equations with no coupling

variable. FM 2.2 is the same as FM 3.1. The user has quantitative justification for determining that FM 2 and FM 3 are coupled. Featuring FMs and their related parent-child equations during the decomposition process can remove the need to make judgment calls about possible coupling while developing the design matrix and determine the location of coupling. In cases where there are repeated variables, there is quantitative justification for the coupling and the location of the coupling is evident.

3. Discussion

It should be noted that potential ROI was chosen as the top level FM in the design solution as opposed to ROI. In a SME similar to the customer in this paper, the expected ROI is not guaranteed. An order is accepted and then filled. Between accepting the order and completing it there are a myriad of disruptions that can result in partial or full loss of the expected ROI. As a result, that expected ROI is more accurately a potential ROI if every step between accepting and completing an order goes as

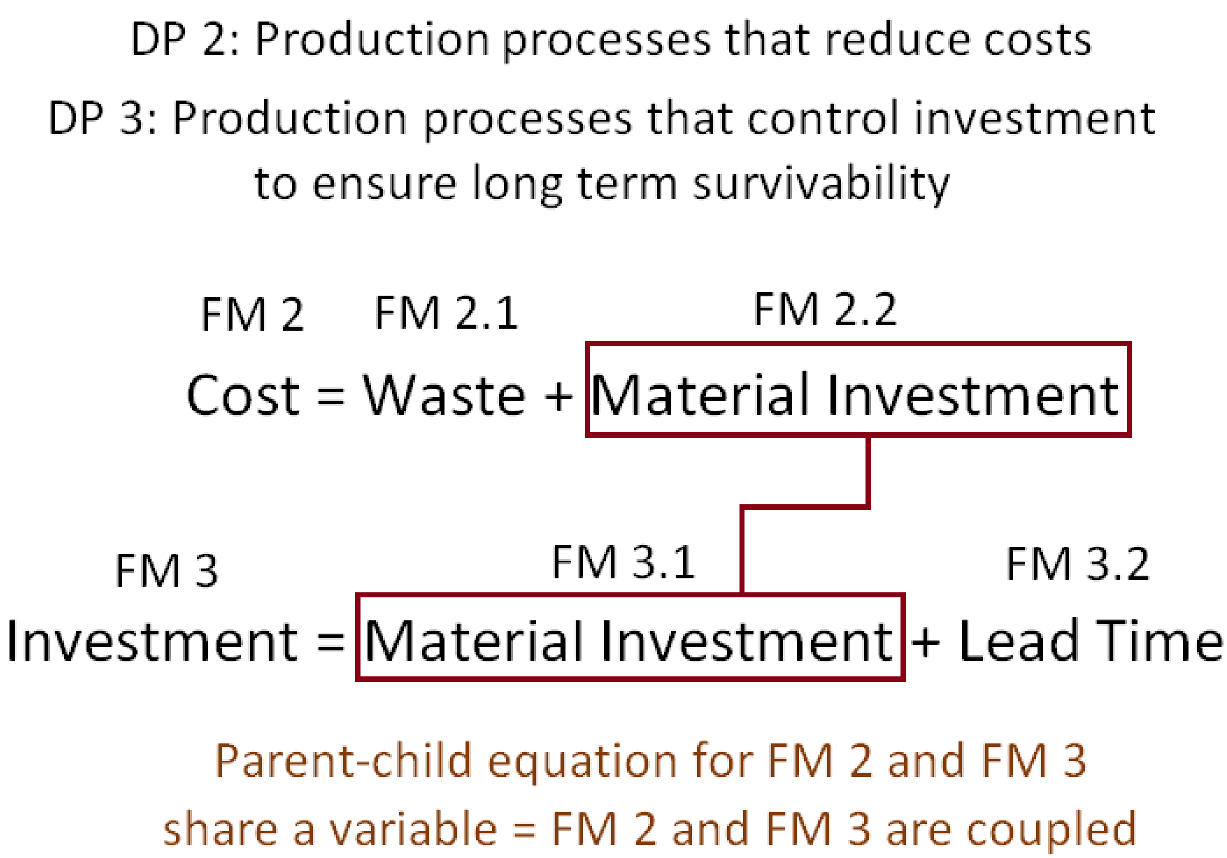

Figure 14: Two FMs and their related parent-child equations with coupling

expected.

A derivative over time is measured for each FM. It might be best to think of it as an identical decomposition of the FM column but instead of FM 0 being PRO, it would be:

FM 0: dPROI / dt

These time derivatives show a trend for each FM and can be useful when the design solution or parts of the design solution are not performing within acceptable tolerance. The user can monitor which FMs are trending in an undesirable direction and can then determine whether to improve the standard work, choose a new DP, or choose a new FM FR pair. In the case of needing to choose a new DP or FM FR pair,

FMs and their related parent-child equations can facilitate determining what new DPs or FM FR pairs need to be present to maintain CEME.

The iteration of the design solution in this work featuring FMs at every level is similar to Cochran's (2002) MSDD in some ways. MSDD could be considered the benchmark for an axiomatic design based template used for developing an effective and efficient SME and was one of the inspirations for this work. The iteration in this work that features FMs at every level could be used by order accepting SMEs, similar to how Cochran's (2002) MSDD serves as a template that multiple SMEs currently employ. The second iteration in this work could be seen as an improved design over MSDD based on the rationale that it remains CEME while containing fewer FRs. The second iteration in this work also features FMs on every FR, while Cochran's MSDD does not.

Featuring FMs for each FR could be considered a return to and expansion of Suh's original decomposition process. In his books, Suh (1990, 2001) has a FM for each function in his example decompositions and often a physical metric on the DPs. Suh's (2001) ROI decomposition features FMs and parent-child equations and is the basis for both the design solution iterations in this work and Cochran's (2002) MSDD. Even in his often cited example of the faucet controlling both flow (Q) and temperature (T), there are FMs. Though FMs and their related parent-child equations are not explicitly used or mentioned in that example, it could be said that there is an understood parent-child equation. One could consider the top level FM:

FM 0: Hand cleanliness = f (Flow, Temperature)

Cleanliness could be considered a function of flow and temperature, FM 1 and FM 2 respectively.

FMs are their related parent-child equations can facilitate decomposing in a solution neutral environment. One problem that can occur during the decomposition process is the inclusion of physical data in the FR. Dickinson and Brown (2009) write on the importance of decomposing functions in a solution neutral environment. Thompson (2013) writes of the procedural error that designers can make of including physical information in higher level FRs. Starting with a FM and defining a FR, which is "control [FM X]," can help users avoid the inclusion of physical information in the FR.

The use of FMs and their related parent-child equations can facilitate communication between designer and user. There can be times when a user is not sure of exactly what they need at each level of a design solution. The designer wants to give the user what they need and therefore has to rely on the user being able to at least partially articulate what they need. However, if the user knew exactly what they needed to control and how, it could be argued that they would not need a design solution developed in the first place. FMs and their related parent-child equations remove the need for the user to be able to articulate every function they need controlled.

4. Conclusions

The use of FMs and their related parent-child equations can facilitate the decomposition process. FMs and their related parent-child equations provide quantitative justification for identifying how many children each FR DP FM pair should decompose into while maintaining CEME. Furthermore, they facilitate identifying whether certain expressed CNs should be present in the decomposition and where they should be located.

The use of FMs and their related parent-child equations can simplify the decomposition process. Parent-child equations can facilitate identifying coupling, reducing time spent developing the design matrix. In cases where no parent-child equations share a repeated variable, there is a quantitative justification for concluding that there is no coupling without using the design matrix at all. In cases where there are repeated variables, the location of coupling can be quickly identified without requiring the user to make judgment calls.

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Chapter 5: Synopsis

1. Introduction

1.1 Objective

As stated in Chapter 1, the objective of this work is to study using functional metrics (FMs) in Axiomatic Design (Suh 1990), their relationship to each other within the functional domain, and ways in which they add value to the design process and the design solution, as well as variables that influence that value.

The scope of this work is defined in Chapter 1 as situations in which the top level FM is related to improving return on investment (ROI).

1.2 Rationale

AD provides a process for developing design solutions that provide a user control of a top level function. The level of control is defined as how close the actual output of a design solution is compared to the expected output based on a specific input. If the actual output is equal to the expected output, the design solution is in complete control. In a design solution, the values of the FMs at the lowest levels can be considered the input. The value of the FMs at higher levels can be considered output. Collectively exhaustive, mutually exclusivity (CEME) is a defining factor of a design solution that provides the user control. CEME means that a design solution includes every function that affects the top level function and that each function is controlled independently. Customer needs (CNs) are traditionally collected to determine which lower level functions need to be controlled to satisfy the top level CN. CNs are then translated into the functional domain as functions that need to be controlled or into the physical domain as design parameters that can be adjusted to control a function.

AD might be challenging for some users during the decomposition process, especially newer users with limited experience decomposing. It might be difficult to determine which domain a CN should be mapped to. Also, it might be difficult to determine which other functions not expressed by the customer should be present to develop CEME design solution. Dickinson and Brown (2009) suggest using a theme during the decomposition process. They write that the use of a theme can facilitate the user determining whether all the functions that need to be controlled have been included. However, a theme can be qualitative and might not provide quantitative justification for a CEME design solution.

FMs and their related parent-child equations can facilitate determining which lower level functions need to be controlled to provide control of the top level FM. As is often the case with an equation, the value of the dependent variable is controlled by the value of lower level independent variables. Likewise, the variables in a parent-child equation show the designer which FMs need to be controlled at the immediate lower level.

FMs can help determine possible functions being unnecessarily controlled in an existing design solution that do not affect the top level FM. It is possible that a customer does not know exactly what they want or that they might not accurately express what they want. A customer might express lower level CNs that have no effect on the top level CN.

Similarly, a customer might not express a CN that is required for a CEME solution. During the process of mapping CNs to FRs, DPs and constraints, essential functions for a CEME design solution might not be included. Parent-child equations can facilitate identifying unexpressed FMs that might appear in a parent-child equation even though it was never expressed by the customer.

FMs can help determine how successfully each function is being controlled. Full control of a design solution can be defined as no variation between the actual output of a design and the expected output. Without a FM for every FR DP pair, design solutions might be similar to an open loop system (Figure 1). A specific input is applied and the result is an output that might or might not be within the acceptable tolerance for the desired output. An example is a water sprinkler for watering the lawn. A sprinkler is set for a defined time and waters the lawn for that time. There is no measurement of how successfully the sprinkler watered the lawn. No correction is made to improve how successfully the sprinkler distributes

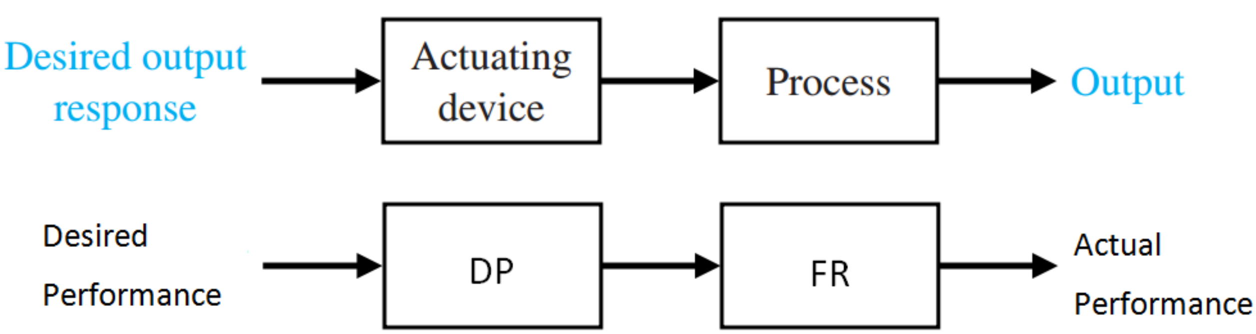

Figure 15: Open loop control system

the water on the lawn. Similarly, without FMs for every FR DP pair, it could be difficult to tell which functions in the design solution are out of control and to what degree.

FMs and their related parent-child equations can facilitate improving control of a design solution in two ways:

(1) Showing when a design solution is out of control
(2) Showing which specific functions in the design solution are responsible for the lack of control

A design solution featuring FMs and parent-child equations is similar to a close looped system. In a closed loop system, there is a desired output (Figure 2). When the design solution is enacted and completes an iteration, the actual output can be compared to the expected output. If the variation is outside of the acceptable tolerance, adjustments can be made to reduce the variation. In design solutions that do not feature FMs at every level, there might be a time when an adjustment is needed but not made. Overlooking the need for an adjustment might be because it is not obvious that the design solution is out of control.

Without understanding how functions in a design solution are quantitatively related to each other, it might be difficult to determine which adjustments need to be made to restore control and when. Parent-child equations facilitate relating lower level FM FR DP pairs to higher level FM FR DP pairs. Having a FM for every FR DP pair shows an actual value for how successfully each function in the design solution is being controlled. The values of a FM can facilitate identifying where the root cause of the lack of control is within the design and make it obvious when control is lost.

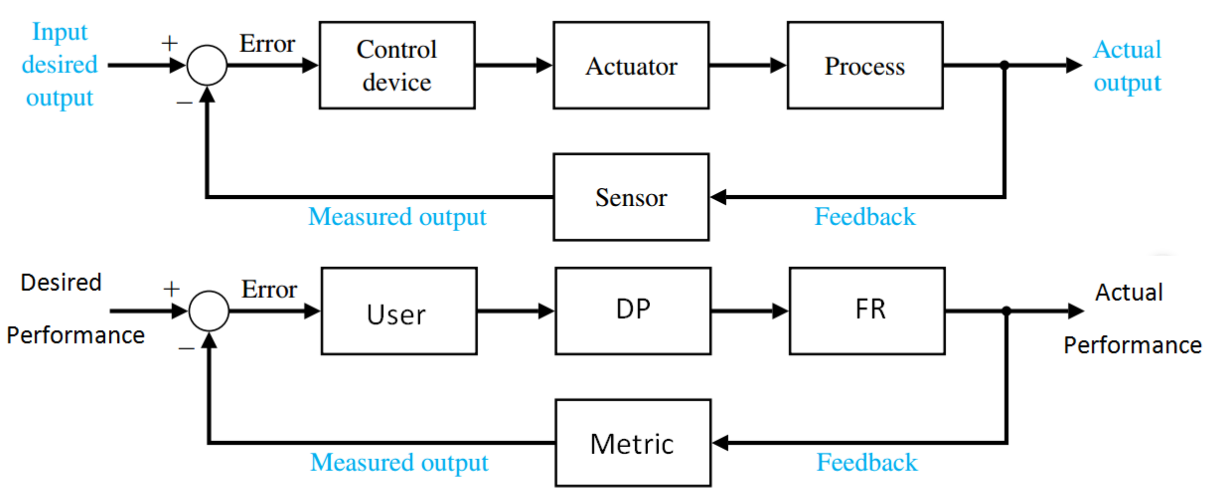

Figure 16: Closed loop control system

2. Discussion

In Chapter 2, two hypotheses are stated and tested using a case study:

(1) That a meaningful functional metric (FM) assigned to every functional requirement could facilitate the development of collectively exhausting mutually exclusive (CEME) design solutions

(2) That parent functional metrics should equal the combination of their children.

Three iterations of a design solution are critiqued, each iteration featuring FMs more predominantly than the previous one. The findings indicate that FMs can facilitate developing CEME design solutions and that child FMs should combine to equal the parent.

Chapter 3 and 4 provide two other cases that support the findings of chapter 2 and further the understanding of FMs. In Chapter 3, FMs and their related parent-child equations facilitate controlling the point differential in American football games. Points are similar to ROI, in that there is a return for cost and investment. The difference is that the return is in points instead of money. In Chapter 4, FMs and their related parent-child equations facilitate controlling the ROI of a SME with the scope limited to the production processes.

There are multiple takeaways from this work that begin with the hypotheses from chapter 2 and become staples of the design process in chapter 3 and 4 about FMs and their related parent-child equations as far as:

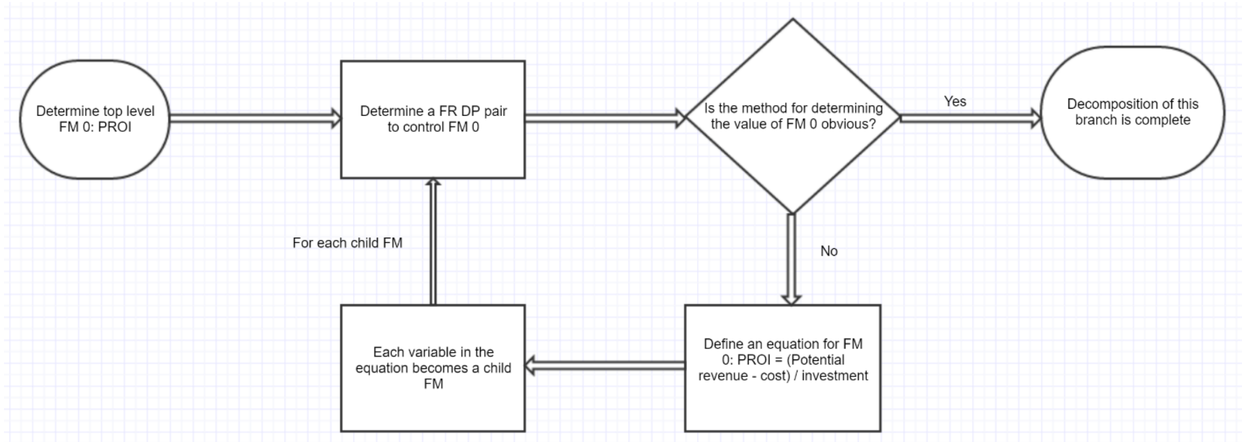

Figure 17: FM decomposition flow chart

(1) How they relate to each other

(2) What value they add to the development and maintenance of CEME design solutions

(3) What value they add to the future of AD

2.1 The relationship between FMs

The relationship between different functional metrics and their related FR DP pairs is defined through the use of parent-child equations.

Children FMs combine to equal the parent. Traditionally in AD (Suh 1990), parent FRs and DPs are said to be the sum of their children FRs and DPs. Using a zig zag decomposition process, suitable DPs are chosen to control each FR. The chosen DP then determines the scope of the immediate lower level of FRs, which should be collectively exhaustive (CE) with respect to the parent FR and mutually exclusive (ME) with respect to each other. Parent and children FMs have a similar relationship (Figure 3). Once a top level FM is determined, a FR DP pair is determined for controlling that FM. The FR is a restatement of the FM stating that the function is to control the related FM (Henley 2016). For example:

FM 0: ROI

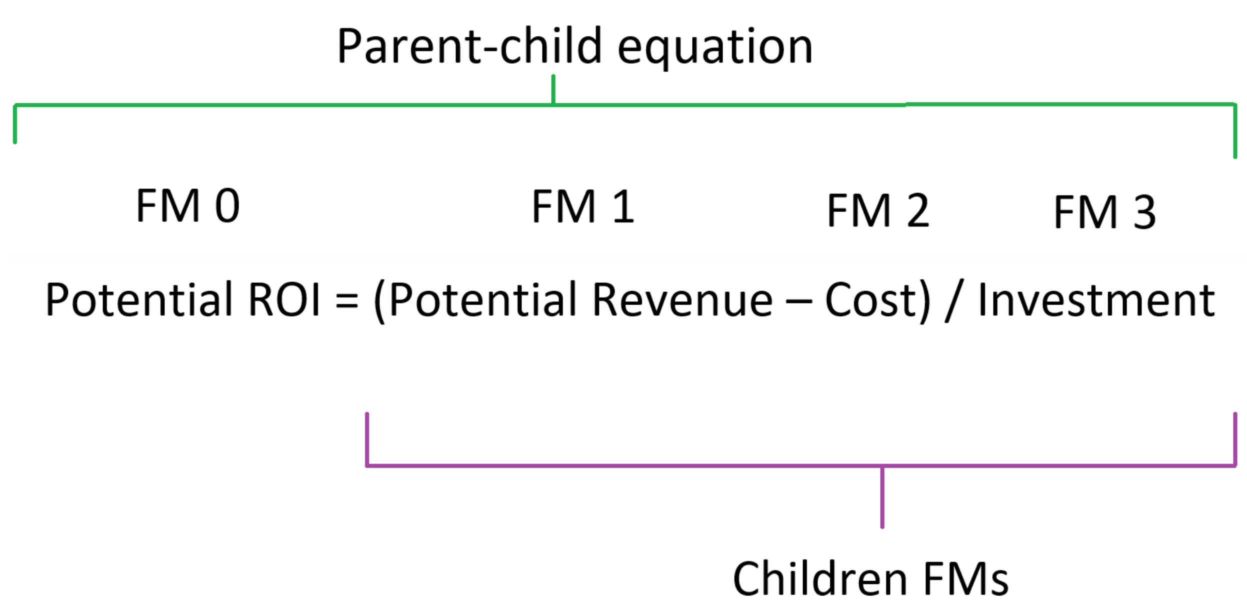

Figure 4: FM with parent-child equation

FR 0: Control ROI

A suitable DP is chosen as the method for controlling that FM. CNs are used as constraints when choosing suitable DPs. Similar to the traditional method, the chosen DP determines the scope of what need to be controlled at the lower levels. For example, in chapter 4, the top level FM FR DP pair is:

FM 0: Potential ROI

FR 0: Control potential ROI

DP 0: Production processes that prioritize long term ROI

There are many processes within a small manufacturing enterprise (SME) that affect ROI. In this case, the DP limits the scope of what is being controlled to the SME's production processes. Even though there are processes outside of production that affect ROI, the next level of FM FR DP pairs can be considered CE with respect to the parent and ME with respect to each other if all of the production processes affecting ROI are being controlled.

Next, it is determined if the method for obtaining the value of the FM is obvious. In the case of PROI, PROI is the combination of and dependent on multiple lower level FMs. Therefore, the method for obtaining complete control of the value is not obvious. As a result, a parent-child equation is defined to determine which lower level FMs PROI is dependent on. Each of the FMs at the immediate lower level is

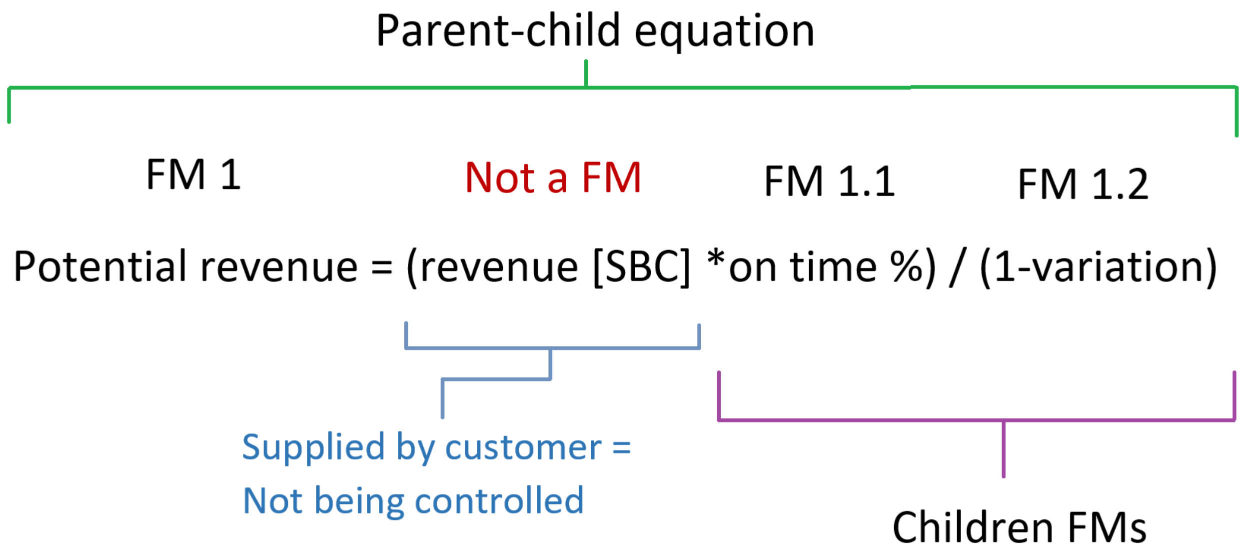

Figure 18: FM with parent-child equation featuring an uncontrollable metric

then independently controlled by its own FR DP pairs (Henley 2015). The process begins again with each FM at the new lower level, determining if the method for obtaining the value of each FM is obvious. This process is repeated until the lowest level. The lowest level is defined as the level at which the method for obtaining the value of a FM is obvious.

2.2 The value that FMs add to the development of CEME design solutions

FMs and their related parent-child equations can add value to the development of CEME design solutions. Furthermore, they can facilitate the long term maintenance of CEME design solutions, when internal or external factors require changes in the design solution. FMs and their related parent-child equations can improve development of a design solution by:

(1) Facilitating the decomposition process
(2) Facilitate the identification of coupling
(3) Providing long term effectiveness
(4) Improving the long term usefulness of the design solution to the user

2.2.1 Facilitating the decomposition process

FMs and their related parent-child equations can facilitate the decomposition process. Parent-child equations relate higher level FM FR DP pairs to lower level FM FR DP pairs. As mentioned, parent-child equations are used to decompose a FM whose method for obtaining the value of a FM is not obvious. After a top level FM, Potential ROI from chapter 4 for example, is determined, the decomposition process begins (Figure 4). Potential ROI is a combination of other lower level FMs. It could be said that potential ROI is the dependent variable and the lower level FMs are the independent variables in a parent-child

#	[DP] Design Parameters	[FM] Functional Metrics
0	Production process that prioritize long term ROI	PROI = (Potential revenue (PR) - cost) / investment
1	Production processes that consistently provide customer satisfaction	PR = Revenue [SBC] * ((On time % (OTP)) / (1 - variation (V))
1.1	Production processes that consistently provide expected output	V = Design variation (DV) + production variation (PV)
1.2	Production processes with minimal disruption	OTP = Expected completion time (ECT) [SBC] / (ECT [SBC] + (Response time (DRT) * # disruptions (ND)))
1.2.1	Rapid disruption reaction system	DRT = Time to recognize + time to contact problem resolvers (TTC) + time to resolve (TTR)
1.2.1.1	Measurement of output after each step in production	DRD
1.2.1.2	Defined easy to access communication paths to problem resolvers	TTC
1.2.1.3	Standardized methods for resolving each disruption cause	TTR

Figure 19: Lowest level FMs

equation. The parent-child equation shows the relation between FM 0: PROI and the FMs at the next level:

(1) Potential revenue

(2) Cost

(3) Investment.

A parent-child equation facilitates determining which functions need to be controlled at the next level of a CEME design solution. In Figure 4, there are three controllable independent FMs in the parent-child equations. As a result, there must be 3 FMs at the next immediate level. Each FM at the next level is one of the controllable independent variables from the parent-child equation from the level above:

FM 1: Potential revenue

FM2: Cost

FM 3: Investment

The process repeats at the next level for FM 1: Potential revenue (Figure 5). Each controllable independent variable becomes a FM at the immediate lower level. There is one exception to this rule. In the parent-child equation in Figure 5 there are 3 independent variables:

(1) Revenue

(2) On time %

(3) Variation

In this case, revenue is supplied by the customer (SBC) and not controllable within the design solution. As a result the next immediate level has 2 FMs, the controllable independent variables:

FM 1.1: On time %

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ 0 & X & 0 & 0 & 0 \\ 0 & 0 & X & 0 & 0 \\ 0 & 0 & 0 & X & 0 \\ 0 & 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \end{bmatrix} \quad \begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ X & X & X & 0 & 0 \\ X & X & X & X & 0 \\ X & X & X & 0 & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \end{bmatrix} \quad \begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 & 0 \\ X & X & X & X & X \\ X & X & X & X & X \\ X & X & X & X & 0 \\ X & X & X & 0 & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \end{bmatrix}$$

A B C

Figure 20: Uncoupled, partially coupled and fully coupled matrices

FM 1.2: Variation

As mentioned previously, the decomposition process continues until the lowest level of FMs. Figure 6 shows the lowest level of one of the branches in the design solution for chapter 4. FR 1.2.1: “Response time” can be decomposed into 3 lower level FMs:

FM 1.2.1.1: Disruption recognition delay time

FM 1.2.1.2: Time to contact problem resolvers

FM 1.2.1.3: Time to resolve the problem

These three FMs are not the combination of any other variables and are instead just measurements of time which can be collected. The method of measuring the value of these FMs is obvious. Therefore, these FMs are the lowest level of that branch in the decomposition.

2.2.2 Facilitating the identification of coupling

FMs and their related parent-child equations can facilitate identifying coupling. Often in AD, a design matrix is used to identify and note the location of coupling during the decomposition process. The

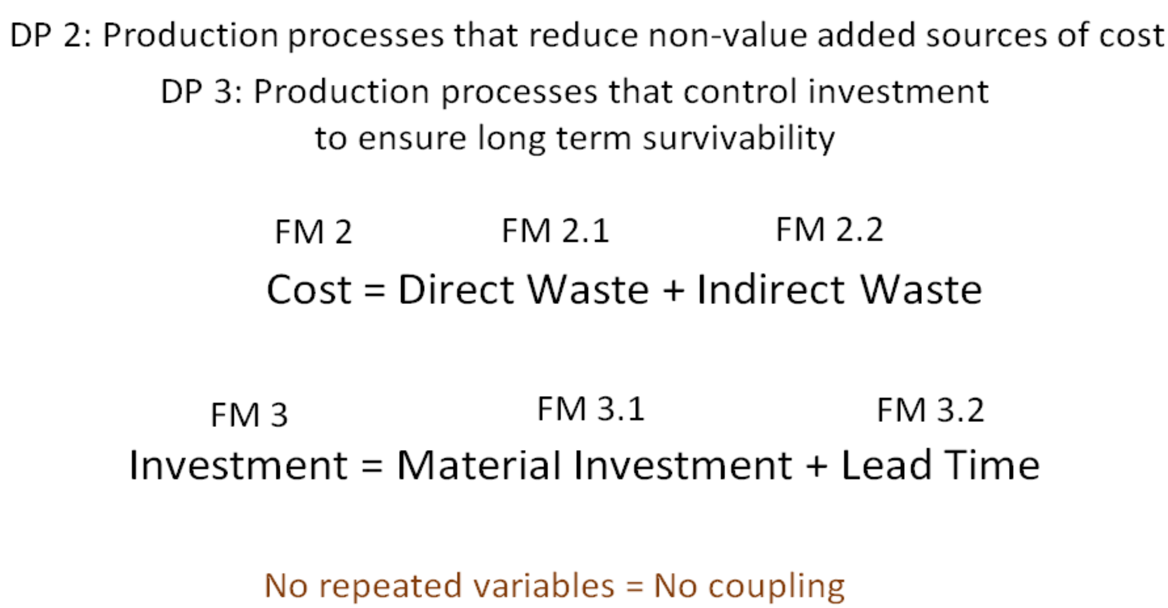

Figure 21: Uncoupled FM FR DP pairs

user considers the adjustment of each DP in the design solution and notes which FM FR DP pairs have the value of their FM affected as a result. It should be noted that the value of parent FMs are expected to be affected when the DP in a child FM FR DP pair is adjusted. This is not to be regarded as coupling. Each FM FR DP pair affected by the DP being considered is marked with an X. Assuming that the design solutions in Figure 7 are collectively exhaustive, Matrix A is a CEME design solution. In a CEME design solution, no other FM FR DP pair is affected by the adjustment of a specific DP other than its own pair, which is called an uncoupled design solution. The only elements in the design matrix labeled with a "X" are those on the diagonal line denoting each DP affecting its own pair. The DPs within the design solution can be adjusted in any sequence to achieve the desired output values in a single iteration.

In some design solutions this is not the case. In those cases, adjusting a DP results in inadvertent adjustments in other FM FR DP pairs. Design matrix B is a partially coupled design solution. In the second row of design matrix B, adjusting DP 2 affects the value of the FM in its own pair and inadvertently affects the value of the FM in the FM1 FR1 DP1 pair. However, all of the non-zero nodes in the design matrix can be contained on one side of the diagonal line that denotes each DP affecting its own

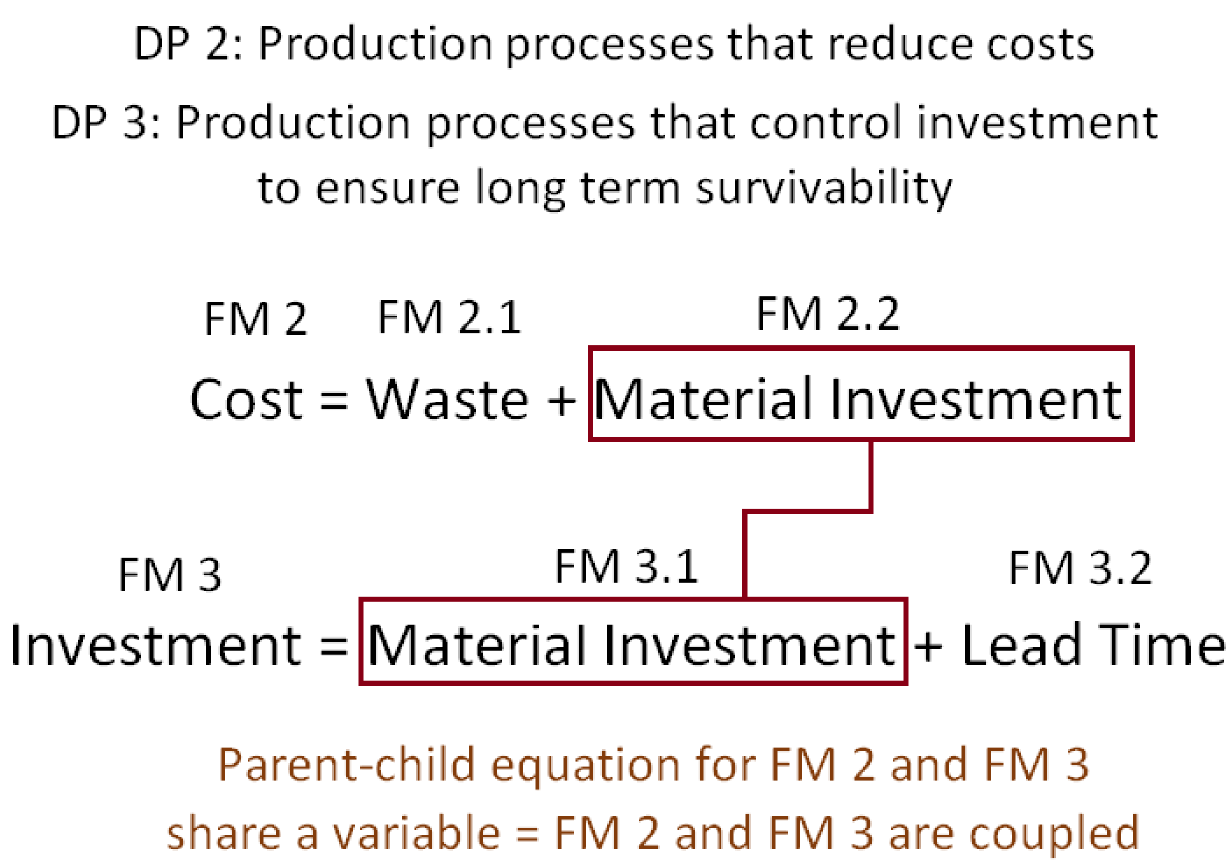

Figure 22: Coupled FM FR DP pairs

pair. Adjustments cannot be made in any order, but there is an order of adjustments that can be followed to arrive at the desired output values in one iteration.

Design matrix C is a fully coupled design solution. In a fully coupled design solution, adjusting DPs affect other FM FR DP pairs to a degree such that the non-zero terms in the design matrix cannot be isolated on one side of the diagonal non-zero term line. As a result, there is no order of adjustment in which the desired output values can be achieved in one iteration.

FMs and their parent-child equations can reduce the time spent developing a design matrix. Some users might find the design matrix inaccurate and time consuming. Without FMs and their related parent-child equations in the design solution, there might be situations in which users would have to make a judgment call about the presence of coupling. As mentioned previously, parent-child equations relate parent FMs to child FMs. In addition, parent-child equations can show possible relations between sibling FMs or FMs in different parts of a design solution. Variables within parent-child equations can provide quantitative justification for determining coupling.

Figure 8 and Figure 9 are examples of FMs and their parent-child equations providing quantitative justification for the determination of coupling. In this work, DPs limit the scope for their related FMs and parent-child equations. In Figure 8, DP 2 limits the scope of cost to non-value added sources of cost, sometimes called waste. DP 3 limits the scope for its FM and parent-child equation to production processes that control investment to ensure long term survivability. FM 2 and FM 3 each have a parent-child equation. FM 2's parent-child equation variables are:

FM 2.1: Direct waste

FM 2.2: Indirect waste

FM 3's parent-child equation variables are:

FM 3.1: Material investment

FM 3.2: Lead time

None of the variables in the two parent-child equations are repeated. As a result, it can be concluded that there is no coupling between FM FR DP 2 and FM FR DP 3 at this point in the decomposition.

In Figure 9, the FM 2 FR 2 DP 2 and FM 3 FR 3 DP 3 pairs are coupled. DP 3 is the same as it was in Figure 8. DP 2 has been changed to incorporate all production processes that reduce costs not just those that are non-value added. As a result, FM 2's parent-child equation variables are:

FM 2.1: Waste

FM 2.2: Material investment

FM 3's parent-child equation variables are the same as in Figure 8:

DP 3.1: Material investment

DP 3.2: Lead time

FM 2 and FM 3's parent-child equations share a similar variable. An adjustment to DP 2.2 to change value of the "material investment" FM will have to cause a change in the FM 3.1 FR 3.1 DP 3.1 pair. The two pairs are therefore coupled and the coupling is supported by quantitative justification.

2.2.3 Providing long term effectiveness

FMs and their parent-child equations can facilitate developing effective design solutions. There might be situations in which resources are limited and not every part of the design solution can be prioritized. In those situations the user might have to make choices about which FMs should be prioritized resources to get the greatest improvement in the output of the top level FM.

Decision making in American football can be an example of a situation in which limited resources are distributed to gain the greatest improvement in output. If asked, a decision maker on a football team might say that their top level FM is the number of games won in a season. In fact, during press conferences, decision makers have been recorded stating their goal is to win every game each season. Even with same top level FM, "win every game during the season", different decision makers might have different opinions about which inputs should be prioritized resources to best influence that output. However, games won might not be the most suitable top level FM due to low controllability. There are sixteen games each season. Over the history of professional American football, only two teams have ever won every game in a season. It could be said this is a difficult FM to control and there might be a more effective top level FM.

In chapter 3, point differential is determined to be a more suitable top level FM than whatever FMs the decision makers in professional football used to control their wins in the 2015 regular season. Using FMs and their related parent-child equations, two design solutions are developed that control point differential. The first is:

FM 0: Point differential

FR 0: Control point differential

DP 0: Fixed play calling strategy

The second is:

FM 0: Point differential = Points scored – Opponent points scored

FR 0: Control point differential

DP 0: Adaptive play calling strategy

Three teams are used from the 2015 season:

(1) The Seattle Seahawks
(2) The Kansas City Chiefs
(3) The Cleveland Browns

FMs and their related parent-child equations were used to design more effective design solutions than whatever system was used by these three NFL teams during the 2015 NFL regular season. Figure 10 shows the top level FM output of both design solutions when run through a play calling simulator,

Means:	**Actual**	**Fixed**	**Adaptive**
Seahawks			
Points scored	26.44	36.13	31.00
Opponent points	-17.31	-15.50	-21.25
PD	**9.13**	**20.63**	**9.75**
Chiefs			
Points scored	25.31	31.63	33.00
Opponent points	-17.94	-21.88	-20.31
PD	**7.38**	**9.75**	**12.69**
Browns			
Points scored	17.38	25.19	26.94
Opponent points	-27.00	-29.56	-23.63
PD	**-9.63**	**-4.38**	**3.31**

Figure 23: Point differentials for the 2015 season, fixed play calling strategy and adaptive play calling strategy

comparing the actual output from the 2015 NFL regular season. For points scored, which is the FM 1 FR 1 DP 1 branch of the decomposition, the design solutions were more effective.

The design solutions might seem like they were less effective or as effective at limiting opponents' points scored, which is the FM 2 FR 2 DP 2 branch of the decomposition, than the NFL teams were during the season. However, this is due to the score lead of the controlled team. When a team takes a large score lead and the end of the game approaches, the strategy changes. The controlled team allows the opponent to move down the field easier with short to mid-range passes, prioritizing defense against long gains. This is done because the loss of time as the clock keeps running down is more important than short to mid-range yardage gains. As a result the opponent will often score points. This is due the fact that they are able to more easily move into scoring position at the cost of time. It should be noted that due to the nature of American football, each time the number of opponent possessions is reduced by one, the number of possessions for the controlled team goes up by one. These are the rules of the sport and not considered coupling during the development of design solutions. The adaptive play calling strategy was overall more effective than the fixed play calling strategy. The adaptive play calling strategy for the Seattle Seahawks should be considered an outlier because the number of injuries on the team during the simulations to the offensive line was unusually high.

The two design solutions from chapter 3 were also more effective for winning games. As mentioned, a decision maker for a professional football team might say that their goal is to win every game each season. Figure 11 shows the win-loss records for each team during the 2015 NFL regular season versus the win-loss records for the two design solutions. The fixed play calling design solution was 37% more effective than whatever system the Seahawks used, 12% more effective than the Chiefs and 19% more effective than the Browns. The adaptive play calling design solution was 31% more effective than whatever system the Seahawks used, 31% more effective than the Chiefs and 50% more effective than the Browns.

Win-loss records:	**Actual**		**Fixed**			**Adaptive**		
Seahawks	10-6	63%	16-0	100%	+37%	15-1	94%	+31%
Chiefs	11-5	69%	13-3	81%	+12%	16-0	100%	+31%
Browns	3-13	19%	6-10	38%	+19%	11-5	69%	+50%

Figure 24: Win-loss records for the 2015 season, fixed play calling strategy and adaptive play calling strategy

2.2.4 Improving long term usefulness of the design solution to the user

FMs and their parent-child equations can improve the long term usefulness of a design solution to a user. Over time, a design solution might become less useful to a user. Meyer and Gupta (1984) write of the inevitable obsoletion of any design solution unless it undergoes some form of evolution. Eventually when focusing on improving the control and effectiveness of FMs, the user will reach some maximum capability. Internal or external factors might cause a change making current FMs no longer as valuable to the user. FMs and especially their related parent-child equations facilitate determining the holes in the design solution left by removing certain obsolete FMs. They also facilitate determining where new necessary FMs might fit into a design solution while maintaining CEME.

A derivative over time is continuously monitored for each FM to determine when the design solution needs to be evolved. The derivative can show when the improvement of an FM's effectiveness has become stagnant. This can also show when a FM is trending in an undesired direction indicating a loss of control. It should be noted that it is possible for a time derivative to appear stagnant signaling maximum capability when that is not the case. This situation is similar to reaching a local maximum or minimum and should be considered before deciding to develop a replacement FM.

2.3 The future of AD

FMs and their parent-child equations might add value toward improving AD in the future. It might be said that AD is neither commonly recognized by name nor commonly used. Two possible solutions to this problem might be:

(1) Simplifying AD
(2) Applying AD to fields that large groups of people commonly enjoy like sports

There might be situations in which potential users of AD, discontinue use of AD in favor of less effective design strategies. Professor Christopher A. Brown has remarked that this might be due to axiomatic design not being introduced early enough in life (Personal correspondence Brown 2017). Introducing AD to users during high school or at an even younger age might result in users choosing AD over less effective design strategies. A necessary step to make AD understandable for high school and younger ages must then be to simplify AD.

2.3.1 Simplifying AD

FMs and their related parent-child equations simplify AD. AD features linear algebra in the design matrix. Some students beginning college might not have been exposed to linear algebra in high school. FMs and their related parent-child equations require only an understanding of first year algebra. Future work should be done to reduce AD to an even simpler level. Doing so might improve the retention rate of axiomatic design users.

2.3.2 Applying AD to commonly enjoyed fields of interest

AD could possibly be applied to multiple organized sports. The Oakland Athletics' use of the "on base percentage" metric in baseball to increase their wins is similar to using FMs and their related parent-child equations. The current findings indicate that AD has been applied to football successfully. Soccer and basketball in particular might have certain stats that correlate with points scored but are not being prioritized.

Conclusions

There are multiple conclusions based on the findings in this work:

(1) Parent FMs should be the combination of their children
(2) If the method for obtaining the value of an FM is not obvious, then a parent-child equation should be determined to facilitate obtaining the value of the FM.
(3) The number of children FM FR DP pairs should be equal to the number of controllable variables in the related parent-child equation.
(4) FMs and their related parent child equations can improve development of a design solution by:
   a. Facilitating the decomposition process
   b. Facilitate the identification of coupling
   c. Providing long term effectiveness
   d. Improving the long term usefulness of the design solution to the user

(5) FMs and their parent-child equations might add value toward improving AD in the future by:
   a. Simplifying AD
   b. Applying AD to fields that large groups of people commonly enjoy like sports

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Appendix

Figure 1: Design attempt with FMs assigned to FRs at all levels (from page 63).