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Towards life-cycle measures and metrics for concurrent product development

Biren (Brian) Prasad
Automated Concurrent Engineering (ACE), Spec2Market Solutions,
e-Manufacturing Business Unit, CERA Institute, P.O. Box 3882, Tustin,
CA 92782, USA, http://www.spec2market.com/
E-mail: Prasad@spec2market.com

Abstract: Concurrent engineering needs both a series of measurement criteria that are distinct to each process and a set of metrics to check (and validate) the outcome when two or more of the processes are overlapped or required to be executed in parallel. Since product realization involves concurrent processes that occur across multiple disciplines and organizations, appropriate measures and the methods of qualifying them (called metrics) are essential. The paper describes these life-cycle measures and metrics and how those could be used for gaining operational excellence.

Keywords: concurrent product development, concurrent engineering, life-cycle measures, metrics, X-ability, DFM, CAD/CAM, measurements, product design, process design, performance, quality measures, criteria, efficiency and effectiveness.

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1 INTRODUCTION

Individual processes, activities and steps in a product design, development and delivery (PD^3) process need to be measured, managed and improved. If a team member cannot measure what he or she is talking about, and is not able to express it in a quantitative or a qualitative term, the team knows nothing about it. One cannot impact what one cannot measure. However, if a team member can measure it, and would be able to express it in some quantitative sense (say in numbers or in sets), the person can improve it. Measurements are not new to product design or engineering. Traditionally, to ascertain confidence at an early PD^3 stage, designers are accustomed to physical aids such as hardware prototype, wood/clay model, conceptual model, model making, mock-up, *etc.* These physical aids measure the compliance with respect to the stated specifications. Furthermore, in traditional systems, designers have used documentation (engineering drawings, sketches, prints) to manage the traditional process. They are also quite familiar with the process of 'design review' to improve its functionality. If design changes were necessary, the annotated design was returned to the drawing board and the process of measurement and improvement was repeated. There were rules of thumb that the designers, over time, had become accustomed to using while adding or selecting a design option or a feature. Today, drawing has been, or is, in the process of being replaced by a 3-D CAD system to manage the product design, development and delivery (PD^3) process. Most ad hoc metrics—known then as multitude of good design practices—are formalized today as design for X-ability (DFX, such as design for manufacturability, assemblability, maintainability). X-ability is a generic reference to a life-cycle measure or concern (e.g. ease, economy, flexibility, efficiency, effectiveness) of a product [1]. In computer software products, the term X-ability refers to things like usability, portability, scalability, interoperability, stability, *etc.*

Consequently, an approach to adequately identify these measures and a resolution methodology for making a high-level design-trade-off between the issues involved are required. For product development team

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this may mean establishing metrics and measuring scores of product values that are important for the customers, the company, or for both. Such measures can focus internally on internal customers', or externally on external customers' requirements. Metrics are measures that indicate (in relative or absolute sense) where 'value' has meaning in terms of assessments and evaluations. Choice of the appropriate metrics depends on the availability of data, its incompleteness, overlap, ambiguity, *etc.* Metrics change with time as new data or a new taxonomy picture emerges.

2 RANGE OF ASSESSMENTS—NEEDS

The product realization process is not complete, if certain types of product and process design assessments are not carried out, and their results are not satisfactory [2]. An assessment may exist in qualitative (as design guidelines) or in quantitative manners (such as in numbers and sets). Quantitative measures provide a degree of objectivity in the range of assessments. This may also include existence of certain types of information that are essential for manufacturing, customer satisfaction, or for the company profitability. The range of assessments for mechanical components may include, for example [3]:

- Performance (basic geometry design, functionality, performance design, component's design).
- System Assembly (assembly modelling, DFA/DFM assembly design [4]).
- Manufacturing Precision or Quality (detailed dimensions, roundness, eccentricity, surface finish, texture, quality control (QC), material and process selection, and tolerances).
- Robustness (insensitivity to manufacturing, material, and operational variations).
- Ownership Quality (ergonomics, reliability, diagnosability, testability, and serviceability).
- Product Retirement (disassembly, reuse, recycling).
- Logistics (purchasing, inventory, international use, environmental standpoint, lead-time, cost-drivers), *etc.*

$$\begin{aligned}&\text{Range of Assessments} = U\,[\text{Performance,}\\&\text{System Assembly, Manufacturing Precision or}\\&\text{Quality, Robustness, Ownership Quality,}\\&\text{Product Retirement, Logistics, } \textit{etc.}]\end{aligned} \tag{1}$$

Where U means 'union-of'. Some of the above measures are required for an organization to become lean, while others are to become agile. Metrics for leanness do not imply agility. They are simply a necessary condition. Organization needs a lot of lean capabilities to become agile. Both lean and agile are measurable, but leanness, in particular, is more observable. You can visualize a just-in-time (JIT) system by looking at work-in-progress (WIP) inventory, floor space, or cycle time. Agility is not directly observable (in real time) because it represents flexibility or the ability to change. An analogy could be a distance/velocity. Leanness may be analogous to distance. When someone traverses a distance, its path can be observed. Speed or velocity cannot be observed, but is the rate of change of distance. Agility may be considered the change in rate in moving from one lean state (a distance) to another. This gives the sense of direction. Agility provides a measure of 'dynamics', how fast the change can take place (that is distance traversed) and 'which direction to traverse'. Because agility cannot be easily observed (compared to leanness), it is a difficult concept to measure and for the CE management to grasp. Leanness, on the other hand, is easy to understand because it deals with eliminating wastes, and can be measured and observed using some lean metrics.

This paper provides insight into a number of life-cycle measures and their roles in the PD^3 process.

3 LIFE-CYCLE MEASURES

Life-cycle measures generally fall into the following 7 categories (see Figure 1).

- **Market Research Targets:** These determine the extent to which customer satisfaction prevails in product development. This is commonly listed in the WHATs column of the QFD matrices. Examples of market research targets are strategic planning, product plans, organizational goals, meeting goals, objectives, *etc.*

1. **Built-in Prevention Measures (by Design):** These are measures that are factored-in when the parts were initially conceived to prevent any future mishaps. Examples of built-in measures are error-proofing, design for consistency, design for insensitivity to parameter variations, and design for reliability, *etc.*
2. **On-line Process Measures:** These are metrics that determine the cause of a process malfunction, such as deterioration of product or process area quality, machine failures, *etc.* Metrics are internally focused.
3. **Diagnostic Measures:** These are metrics that ascertain why a product or process is failing to perform as expected. Diagnostic measures determine which features of the structure part, or of the design prototype, are the causes of failures and are introducing out of norm behaviour. In the product area, diagnostic measures might include test results, MTBF (mean time between failures) analysis, FMEA (failure mode and effect analysis), reliability checks, quality indices, *etc.*
4. **Inspection Measures (on-line or off-line):** Inspection measures are less desirable because they commonly deal with fixing a problem. They do not eliminate the

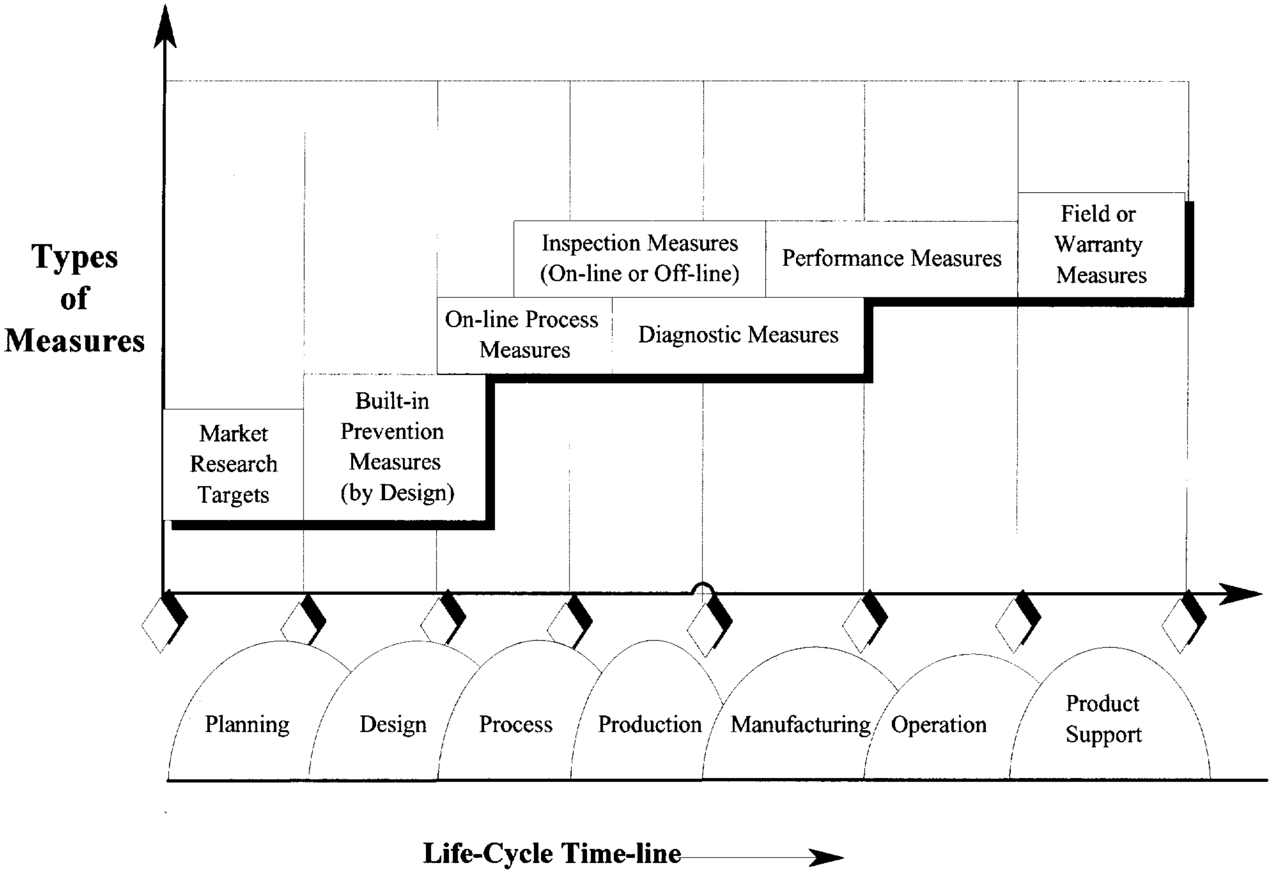

Figure 1 *Common life-cycle measures.*

cause of the problems or detect and eliminate the source of the problems. Because of these reasons, inspection measures are sparingly used in aggressive corporations.

5 **Performance Measures:** Performance measures are high level metrics that assess the overall performance of product, process, team or the enterprise. Performance measures are generally associated with product performance in the field, or in customer use of the products compared to their competitors. These measures are customer focused and are externally based. Examples include productivity, responsiveness, cost, time-to-market, quality content, *etc.* Eight performance indicators are shown in Figure 2 (see [5]). An indicator represents a combined outcome of doing two major efforts in a company: 'doing things right' and 'doing the right things'. Doing things right is measured by the corresponding efficiency of doing 7Ts, 3Ps, 6Ms, or 7Cs [5]. Doing the right things is measured by the corresponding effectiveness of doing 7Ts, 3Ps, 6Ms, or 7Cs (details are given in Table 1). The desired result is the product of the two. The items in each of the two categories and the desired result are outlined in Table 1.

6 **Field or Warranty Measures:** These are metrics that assess the product use in the field in terms of its maintenance, upkeep and warrantee costs. Most measures are customer focused. Examples include customer-found faults, maintenance costs, customer satisfaction index, *etc.*

Some of the above measures are required for an organization to become lean, while others are to become agile. It is assumed that the appropriate measures and metrics are used during product realization process as feedback [3]. Metrics provide answers to a broad range of questions related to the formulation, design engineering, manufacturing and operation. Such metrics must comprise of several life-cycle perspectives, each representing a supplement or an add-on to this collection. Each must contribute to the overall effectiveness of the product realization process.

4 METRICS OF MEASUREMENTS

The success or failure of CE, to a large extent, depends on the team's ability to define useful metrics of measurements (MOMs). Most MOMs include many of the so called 7Ts (talents, tasks, teamwork, techniques, technology, time and tools) characteristics. They measure things that are related to state of completeness of specifications, transformation feasibility, efficiency, performance, effectiveness or goodness (a fitness function)

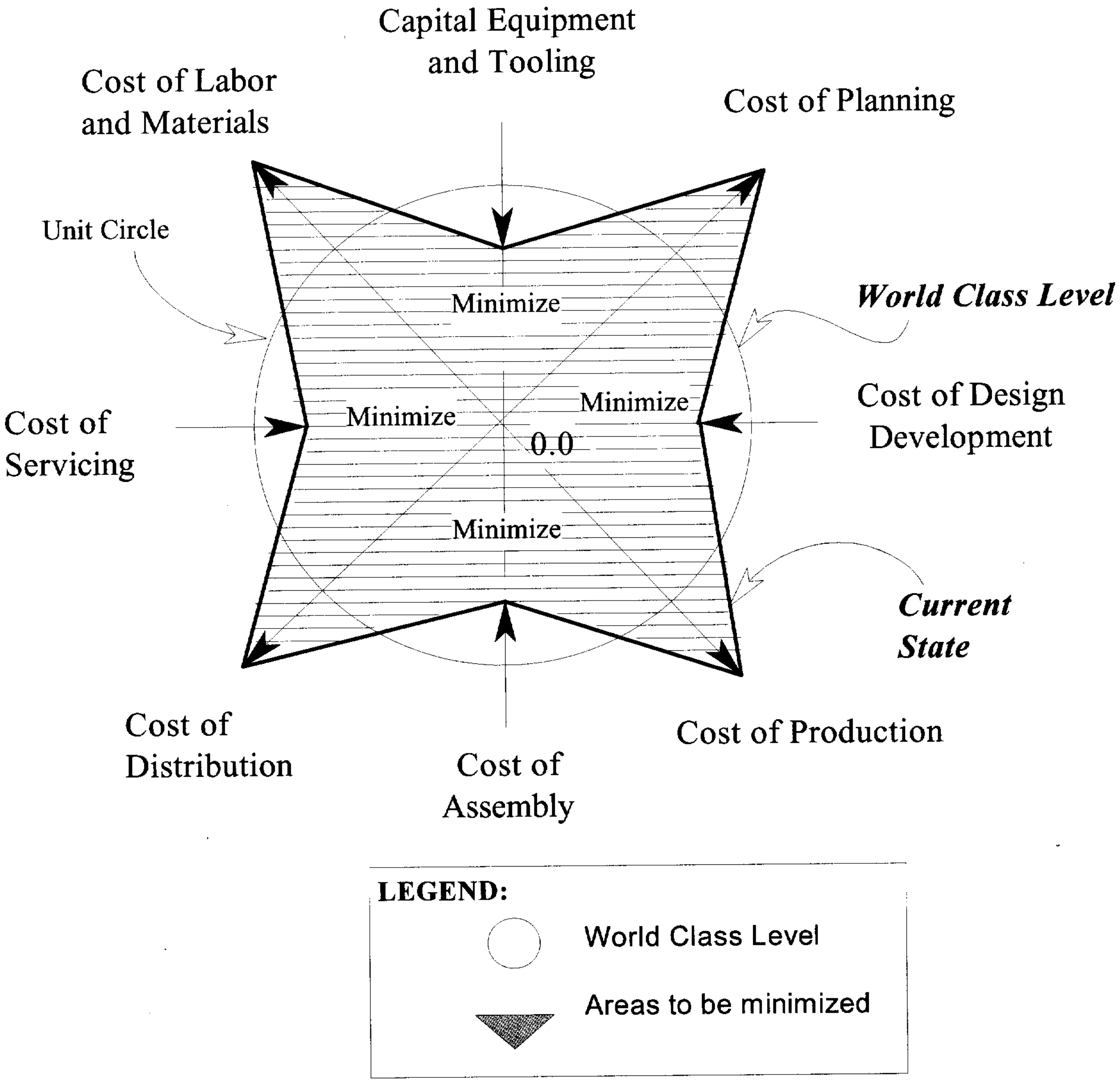

Figure 2 *Performance indicators for measuring an enterprise competitiveness.*

of outputs. If Σ denotes a union-sum of metrics of X-ability measurements, its magnitude will equal one when the artifact is complete (content-wise) and the constraint space is empty.

$$\text{If } \sum \equiv \cup[\{\text{MOMs}\}] \qquad (2)$$

then Σ in Equation (2) $=1$, if artifact is complete (content-wise) and the corresponding constraint space is empty. In Equation (1), it is assumed that each MOM is a normalized set [3].

5 VALUE CHARACTERISTIC METRICS (VCM)

The first step in CE is to develop predictors (metrics for the object systems) and the supporting analysis, tools or concepts for assessing product and process behaviours. Types of analysis, tools or concepts required to assess the value characteristics are contained in Figure 3 [3]. They are categorized according to the level of analysis details required: Identify, analyse, plan, evaluate and performance-to-plan. Many of them are off-the-shelf tools, which a company can buy and integrate. Some tools are 'product specific'; others are 'process specific.' The required analysis tools are categorized in accordance with the needs and purpose—where during the PD^3 process such tools are used and the purpose of using them. The six needs identified during a PD^3 process are: business, design, supportability, production, operation and decision support [6]. The purposes of using the tools have been categorized in accordance with the types of actions taken—to identify, to analyse, to plan, to evaluate, to validate or check performance-to-plan. Four types of CE metrics and measures are contained in Figure 4 [3]. They are arranged in four drawers of a file

Table 1 *Measuring a performance indicator.*

Desired result	= *Doing things right*	× *Doing the right things*
Desired result	Is measured by the corresponding efficiency of doing the following:	Is measured by the corresponding effectiveness of doing the following:
Less unscheduled changes More overall productivity Less time-to-market Less cost-to-quality More profitability Less inventory Better quality Great product Increased safety Increased stability Increased flexibility Increased market growth More customer satisfaction	Integrated product development (IPD) Integrated product and process organization (PPO) 7Ts (*talents, tasks, team, time, technique, technology and tools)* 3Ps (*practices, procedures and policies*) 6Ms (*machine, management, manpower, materials, methods and money)* 7Cs (*collaboration, commitment, communication, compromise, consensus, continuous improvement, and coordination*) * * *	Total value management (TVM) Concurrent function deployment (CFD) QFD (quality function *deployment), TQM (total quality management),* C4 (CAD/CAM/CAE/CIM), *etc.* 7Ts 3Ps 6Ms 7Cs * * *

cabinet. Product development teams (PDTs) can draw upon these metrics to influence PD^3 process. Measures and metrics for product development are categorized into four groups. For example, metrics for X-ability assessment, such as design for manufacturability (DFM) [7] or design for assembly (DFA) [4], design for flexibility can be effective in reducing the number of parts or processes. Metrics for modular design for sub-assembly, design for interchangeability, and design for flexibility can be effective for reducing cost. Product quality and feasibility assessment matrices are used to furnish voices of customers into products, such as features assessment, minimum materials usage, *etc*. Metrics for process quality assessment can be effective for ensuring the product's agility, such as gathering data pertaining to a specification history, performance, precision, tolerances, *etc*. Simulation and analysis (S&A) are also MOMs for driving corrective action, such as material features substitutions or selections, assembly variation analysis, failure mode and effect analysis, risk assessment, *etc*. [5] CE methodology is defined to keep these metrics, measures of merits, and analyses tasks in focus and to provide a desired output. Most of these analysis tasks or concepts, which are quantitative types are contained in the file cabinet (see Figure 4). A few analysis tasks or concepts, not included in the file cabinet, could be a part of a general-purpose conceptual library (similar to what is shown in Figure 3).

A primary advantage of value characteristic metrics (VCM) [3], rather than ad hoc primitive modelling, is that it formalizes and exposes errors and inefficiencies that may be overlooked with the complexity of the product realization process. The VCM based PD^3 process continually monitors CAD progress relative to specifications. It contains influential techniques for getting the attention of designers or processors when parameters appear 'out-of-bounds', or when processes appear 'out-of-control'.

6 BENEFITS OF DEVELOPING VALUE CHARACTERISTIC METRICS

The development of VCM (value characteristic metrics)—as contained in Figure 4—depends upon the 3Ps, 6Ms, 7Ts and 7Cs prevalent in an enterprise. However, their successful use requires their integration into computer-based tools. The two (Tools + VCM) together can serve as measures of merits in checking a variety of DFX compliance. Compliance can be checked for robust design, design optimization, collaborative work, design for manufacture, and design for assembly, to name a few. These developmental metrics can be used for risk reduction, allowing new product concepts to be investigated earlier in their design cycle by all members of an integrated PDT. The clear advantage of developing predictions (such as metrics, computer models or simulations) is that changes or improvements to the total product and process design can be made earlier,

Requirements	Identify	Analyze	Plan	Evaluate	Performance-to-plan
Business	Competitive Assessment, VOC	Market Research	Cost-to-quality	QFD	Organizational Performance
Design	Production Definition Problem Decomposition Multi-disciplinary System Specifications TQM	Robust Design	Concept Generation Cost-to-design	Product Planning Concept Development DFMA Interchangeability	Statistics
Supportability	Specification History	2nd Level Analysis Parametric Optimization	Process Planning Cost-to-supportability FMEA/DFMA FTA	Taguchi's Method Design of Experiments, RMS	Product's Agility Modular Design Reliability
Production	Tolerances	Variational Analysis (VSA) Simulation	Error-proofing Cost-to-error-proofing Mistake-proofing	FMECA	Statistics
Operation	Gathering Data "As-is" Data Flow		Corrective Actions RCM, SPC "To-be" Data Flow	LORA	SPC SQC QC
Decision Support	Economic Analysis	Trade-off Analysis	Cost/Benefit Verification	Cost/Benefit Tracing Tools or Concepts	Cost Benefits Monitoring

Figure 3 *Types of analysis tools or concepts required.*

when costs of such changes are less. X-ability measures can be extracted and captured as a part of such simulation models. Predictive models enable use of simulation at an early stage of design, rather than being forced to use (to handle problems discovered later in the life-cycle) when design is relatively set. The question is how the various designs for X-abilities can be incorporated in the PD^3 process at an early life-cycle stage without impairing important functions, ease, efficiency, flexibility, or feasibility.

In addition to their use in the product realization situations, effective value characteristic metrics do the following:

- Identify process bottlenecks and eliminate root causes of defects.
- Serve as a management tool for assessing and evaluating performance, and efficiency.
- Help teams understand engineering processes better.
- Determine when and where to apply 7Ts (talents, tasks, teamwork, techniques, technology, time and tools).
- Monitor progress during product realization.
- Identify and minimize PPO (product, process and organization) complexity [3].
- Increase objectivity and improve productivity.
- Evaluate your competitors and identify best product features and practices.
- Reorganize the engineering tasks and make critical decisions earlier in the life-cycle.
- Grade performance, categorize changes and move towards trade-off or optimization.

7 CONCLUDING REMARKS

At the heart of any good product design, development and delivery (PD^3) process, there lays the CE focus on satisfying the interests of both the customers and the company. The customer focus shows up in measures (such as market research targets, performance, field or warrantee measures) that a company imposes in response to what customers desire in a product. The company focus shows up in another set of measures (such as built-in prevention measures by design, on-line process measures, inspection measures, diagnostic measures). The paper described a suit of life-cycle measures and metrics. The value characteristic metrics assess the company's ability to manufacture a quality product in less time and cost.

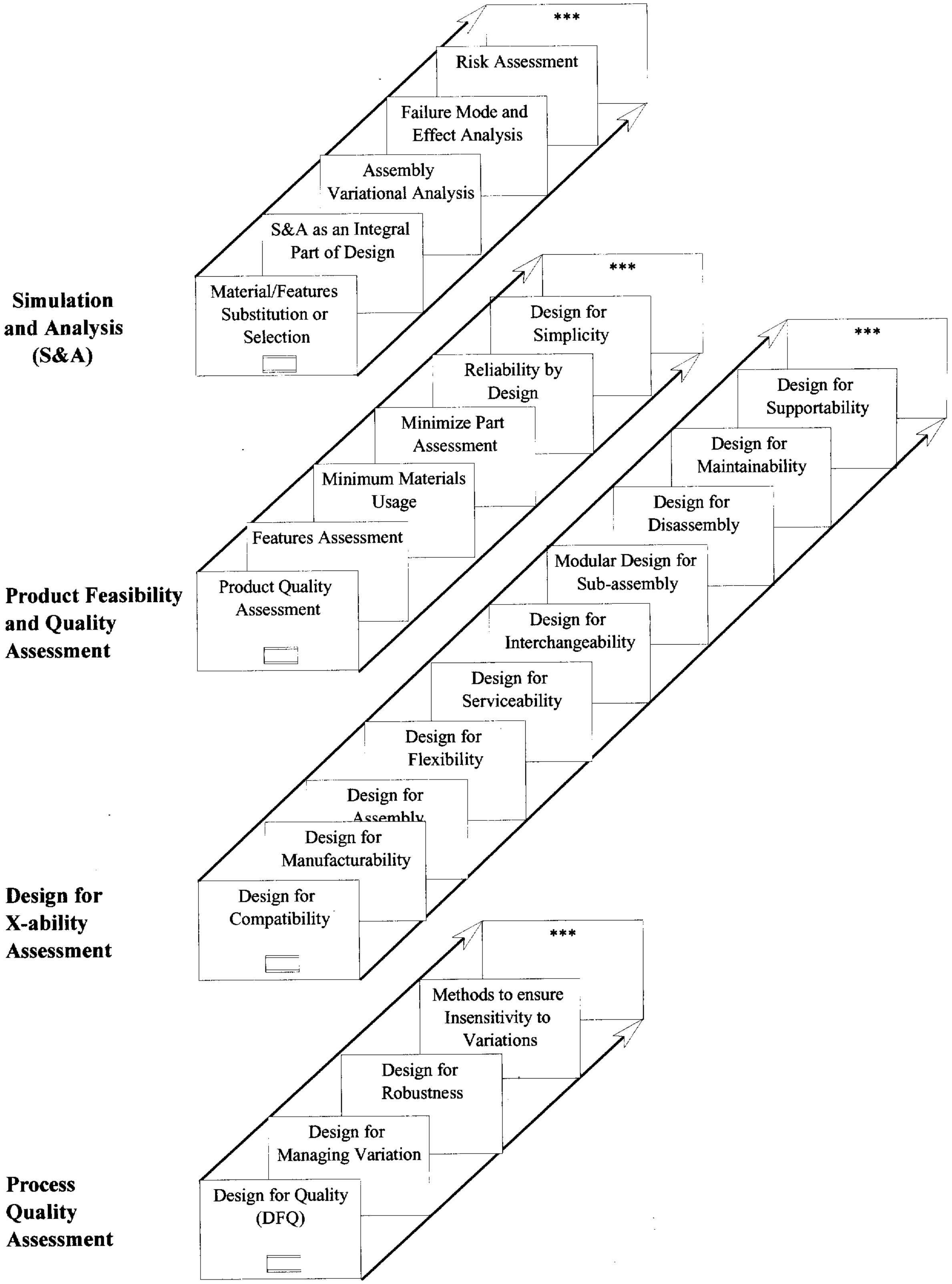

Figure 4 *File cabinet of CE measures and metrics.*

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