

Investment and Resource Allocation Methodology to Support Manufacturing System Design Implementation

D. Cochran, Q. Ng, S. Hendricks, H. Rudolf

Production System Design Laboratory, Department of Mechanical Engineering
Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Abstract

The objective of this paper is to present the development and application of a methodology that applies axiomatic design in the allocation of constrained resources to achieve system design requirements. The method presented is a new approach that leads to the prioritization and selection of improvement projects that have the greatest potential to achieve system design requirements when a company has limited resources.

Keywords: Design, Manufacturing, Investment

1 INTRODUCTION TO AXIOMATIC DESIGN

Axiomatic design establishes a scientific basis for design and is based on two axioms, which differentiate between acceptable and unacceptable system designs. The Independence Axiom states that when there are two or more functional requirements, the design solutions must be chosen so that each functional requirement is satisfied in a predictable way. The Information Axiom states that the specified design solutions chosen should have the highest probability of requirement achievement [1].

Functional requirements (FRs) are defined as the minimum set of independent requirements, which completely characterize the functional needs of the customer. Design parameters (DPs) are the key solutions that logically satisfy the specified set of FRs. The way in which the DPs affect the FRs determines whether the design is predictable and whether the independence axiom is satisfied.

Axiomatic design involves interplay between what we want to achieve (FRs) and how we choose to achieve it (DPs) (see Figure 1) [1].

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & - \\ - & X \end{bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Equation 3 An Uncoupled Design

The second type of design is the path dependent design. This design results in a triangular matrix (see Equation 4) and the independence of FRs can be guaranteed if the DPs are implemented in the proper (path dependent) sequence. The design matrix in Equation 4 shows that DP_1 must be implemented prior to DP_2 to avoid iteration.

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & - \\ X & X \end{bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Equation 4 A Path Dependent Design

Any other form of the design matrix is called a full matrix and results in a coupled design (see Equation 5). A coupled design violates the independence axiom and has a low probability of FR achievement, especially in the presence of DP variation. Such designs often require the designer to repeatedly tweak the DPs in hope of achieving the FRs. Hence, coupled designs create an optimization problem [1].

$$\begin{Bmatrix} FR_1 \\ FR_2 \end{Bmatrix} = \begin{bmatrix} X & X \\ X & X \end{bmatrix} * \begin{Bmatrix} DP_1 \\ DP_2 \end{Bmatrix}$$

Equation 5 A Coupled Design

2 PRODUCTION SYSTEM DESIGN

Professor Cochran and his group at MIT have used axiomatic design to create a framework called the Product Delivery System (PDS), which represents the **design** for a stable manufacturing system that operates with the fewest resources [2]. The PDS represents a system design in its entirety. **Every** FR must be achieved for the design to be complete. W. Edwards Deming, stated, ‘Management objectives cannot be met by unstable systems’ [3]. Professor Cochran defines the six requirements (R) for system stability as:

R1 - Provide a safe, clean, quiet, bright and ergonomically sound environment.

R2 - Produce the customer-consumed quantity every shift (time interval).

R3 - Produce the customer-consumed mix every shift (time interval).

- R4 - Deliver perfect-quality products to the customer every shift (time interval).
- R5 - Do R2 – R4 in spite of operation variation.
- R6 - When a problem occurs in accomplishing R2 – R4, identify the problem condition immediately and respond in a standardized (pre-defined) way.

These attributes for a successful manufacturing system are discussed in a variety of writings [4] [5] [6] [7]. The PDS (see Figure 2) incorporates the six requirements for system stability [8].

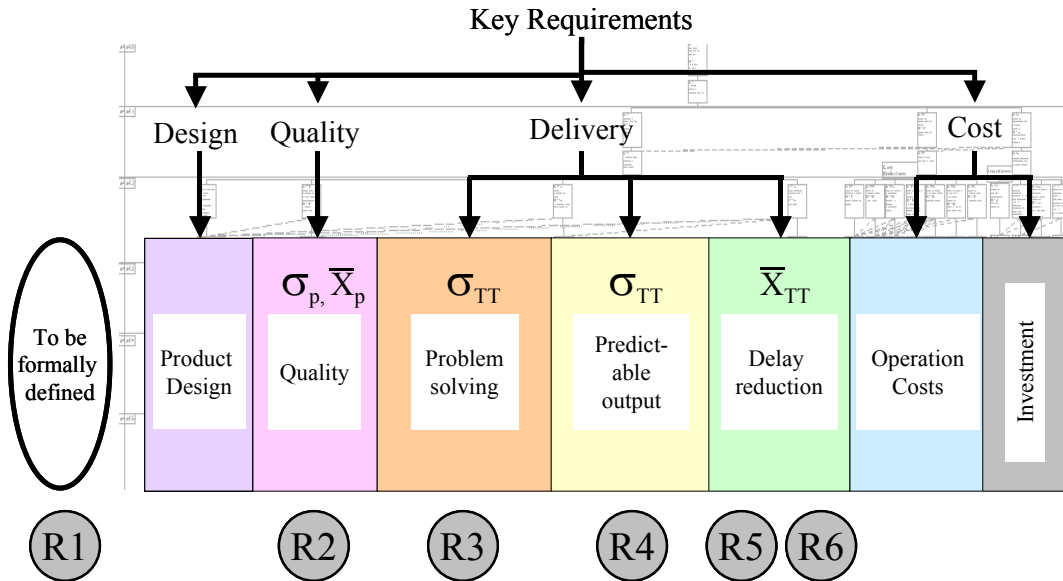


Figure 2 Product Delivery System (PDS) and the Six Requirements for System Stability

The PDS is a path dependent design and clearly illustrates the importance of path dependency in manufacturing system design. Path dependency indicates that an FR is a function of multiple DPs. The high level branches of the PDS are path dependent (see Figure 3) [2].

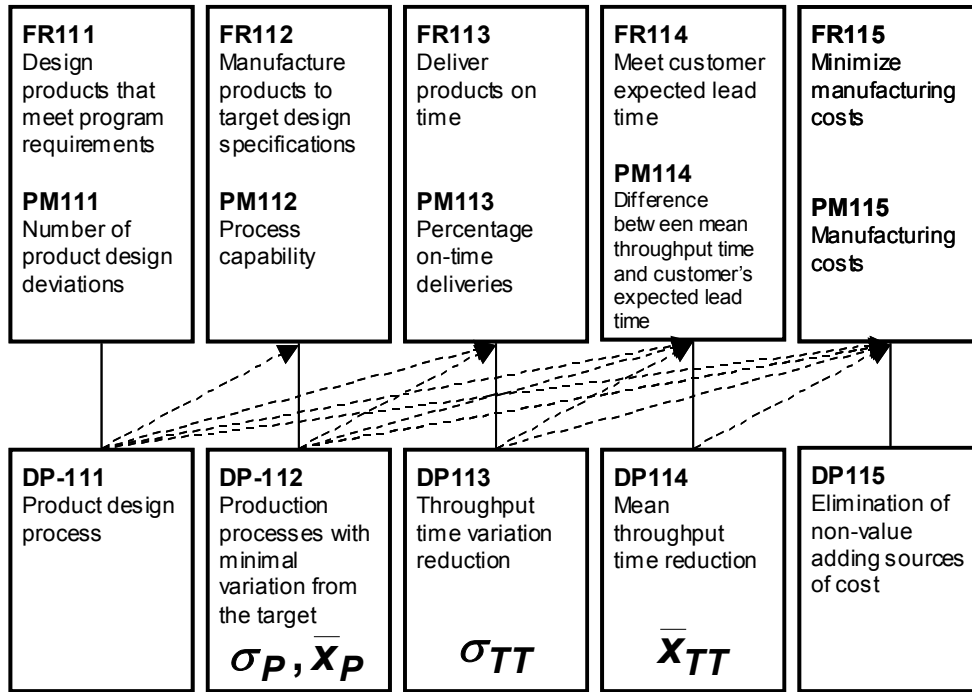


Figure 3 High Level Path Dependent Design of the PDS

The path dependent design describing the FR-DP relationships in Figure 3 is the following:

$$\begin{Bmatrix} FR-111 \\ FR-112 \\ FR-113 \\ FR-114 \\ FR-115 \end{Bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 & 0 & 0 \\ A_{21} & A_{22} & 0 & 0 & 0 \\ A_{31} & A_{32} & A_{33} & 0 & 0 \\ A_{41} & A_{42} & A_{43} & A_{44} & 0 \\ A_{51} & A_{52} & A_{53} & A_{54} & A_{55} \end{bmatrix} * \begin{Bmatrix} DP-111 \\ DP-112 \\ DP-113 \\ DP-114 \\ DP-115 \end{Bmatrix}$$

Equation 6 High Level PDS Design Matrix

The Industry Problem

Industry traditionally lacks a scientific basis for determining the minimum requirements and key solutions to achieve a stable and efficient manufacturing system. Thus it struggles to achieve the six requirements of system stability by blindly throwing resources into successive waves of "improvement projects." That spending leads, consequently, to higher manufacturing costs [9] [10]. The PDS provides a scientific basis for identifying and selecting genuine improvement projects that will fulfill requirements without increasing costs [2].

The ‘health’ of an existing manufacturing system design can be evaluated with a questionnaire based on the PDS [2]. When an FR as defined by the PDS is not fully achieved, unnecessary system instability and cost are incurred. Cost is the direct result of the system design [11]. Only when the manufacturing system is stable can waste be permanently reduced. When true waste is reduced, true cost is reduced [2] [9] [10]. DP implementation to fully achieve the FR often requires additional investment and/or resources. Industry commonly assumes the cost/investment of fully implementing a DP to be prohibitive. Thus, companies unknowingly and inevitably have much higher cost resulting from system instability (e.g. fighting fires, expediting, holding ‘what-can-we-make-today meetings,’ making defective products, etc.) [3].

3 INVESTMENT AND RESOURCE ALLOCATION METHODOLOGY DERIVATION

The goal of the enterprise **must be** to fully achieve the system design requirements as stated in the PDS [2]. Only upon achievement of the system design requirements can cost be reduced. In situations where the enterprise’s resources are constrained, knowledge of path dependency in the PDS design matrix can be used to develop an investment and resource allocation methodology. This methodology enables management to prioritize and select improvement projects based on their sensitivity with respect to FR achievement.

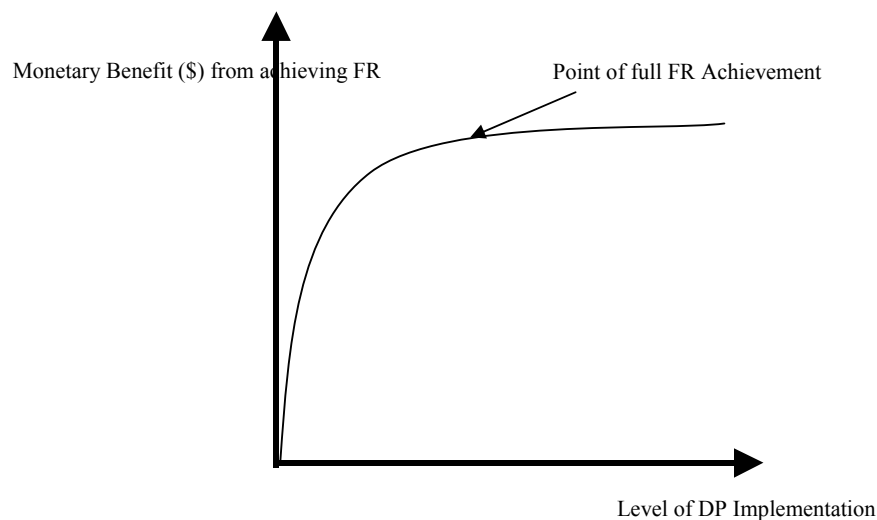


Figure 4 Benefits in FR resulting from DP implementation

As a foundation for this methodology, the FRs and DPs are related to measurable monetary units. Investment (IV) in a DP results in benefits (BF) from achievement of the FRs (see Figure 5).

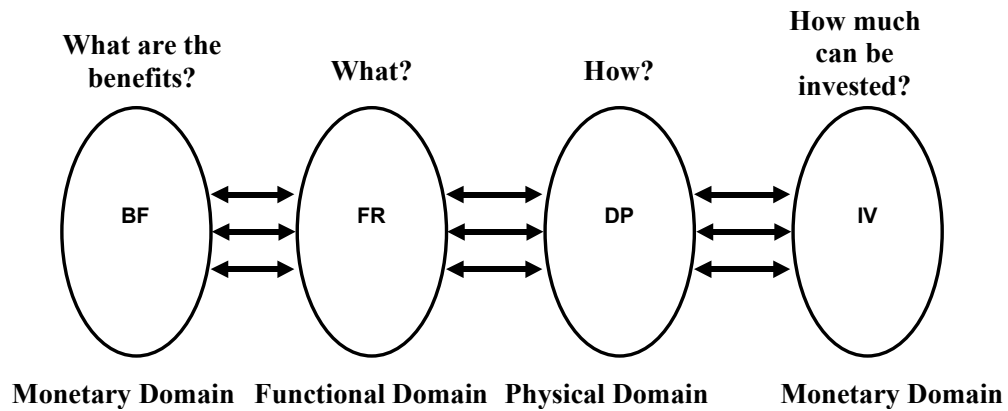


Figure 5 Conversion process from monetary investment to monetary benefits

The current state of each FR must be known and full achievement of each FR is the goal [2]. Higher FR achievement will result in benefits that can be monetarily quantified. Improvement in FR achievement requires investment towards its path dependent DPs. In other words, instead of assuming that "the end (FR) justifies the means (DP)" in a static sense, the PDS drives one to consider how investment in DP's can creatively extend the range of an FR, so that it is more proper to assume that "the means is the end in the making" [9]. Comparing estimated benefits to the required investment enables effective utilization of limited resources.

In order to quantify the relationships between FRs and DPs, performance measures for both are a preliminary necessity. FR achievement can be quantified by the performance metrics defined in the PDS.

A new cost matrix [R] is derived (see Equation 7) to quantify the benefits (BF) resulting from investments (IV). R_{ij} is an expression in monetary units of the sensitivity of benefit resulting from the increase in FR_i achievement caused by investment in DP_j (i.e. return on investment from investing in DP_j).

$$R_{ij} = \frac{\partial BF_i}{\partial FR_i} * \frac{\partial FR_i}{\partial DP_j} * \frac{\partial DP_j}{\partial IV_j} = \frac{\partial BF_i}{\partial IV_j}$$

↓

A_{ij}

Equation 7 Differential Form of Cost Matrix Element

4 SIMPLIFIED MODEL – SINGLE FR-DP PAIR

For a linear design, the design matrix elements (A_{ij}) are constants; for a nonlinear design, A_{ij} are functions of the DPs [1]. It is the authors' belief that most A_{ij} are not constant over the range of implementation, but vary in shape. In practice, companies will be able to use any baseline cost curves they have developed, and as they undertake a continuous portfolio of projects, they will be able to establish cost curves for each FR. For simplicity in model development, the A_{ij} functions have been assumed to take the shape of normal cost curves.

The following model is based on two assumptions:

1. In order to simplify the model, one DP only affects one FR (Section 4 only).
2. The occurrence of investment and benefit are at the same point in time. In reality the benefits will be realized at a later point in time and discounted.

The formula of the R-element is partitioned (see Equation 8).

Benefit received by
achieving FR_i caused by
improving one DP_j

$$R_{ij} = \frac{\partial BF_i}{\partial FR_i} * \frac{\partial FR_i}{\partial DP_j} * \frac{\partial DP_j}{\partial IV_j}$$

↑

↓

Improvement in one DP_j
caused by investment in DP_j

Equation 8 Partitioned R element

Figure 6 below depicts the sensitivities of the two components in R_{ij} . To express both components with the monetary term in the numerator, the second component ($\partial DP_j / \partial IV_j$) was inverted. This graph is based on the assertion that investment in a DP can only become prohibitive once the FR has been fully achieved in the eyes of the internal and external customers. Therefore, the point of intersection represents the absolute full FR achievement. In other words, an additional dollar should be invested in DP_j as long as the benefits are greater than the investment at any point in time.

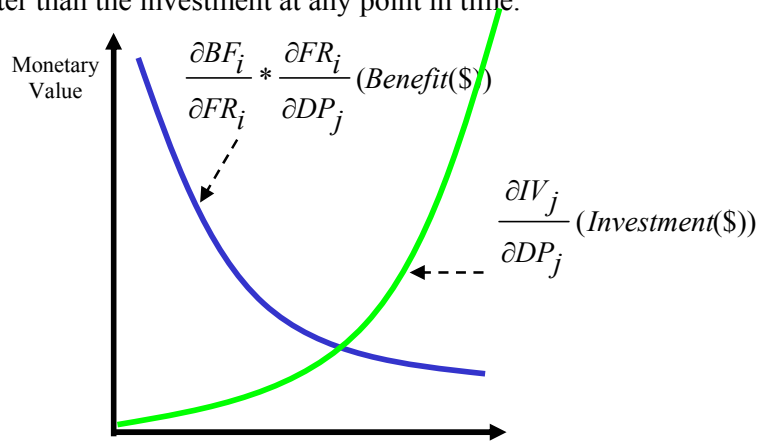


Figure 6 Sensitivity of Benefit to Investment

The curves in Figure 6 are based on the following assumptions:

1. The amount of further benefits to be gained from higher FR_i achievement declines with increasing levels of DP_j implementation.
2. The amount of investment required to improve DP_j increases with higher levels of DP_j implementation.

These assumptions are believed to be generally applicable but must be examined in future case studies.

Incremental investment in a DP is profitable in the region to the left of the point of intersection in Figure 6. The mathematical expression for this statement is:

$$\frac{\partial IV_j}{\partial DP_j} \leq \frac{\partial BF_i}{\partial FR_i} * \frac{\partial FR_i}{\partial DP_j}$$

Equation 9 Investment Performance Sensitivity

or restated:

$$R_{ij} = \frac{\partial BF_i}{\partial FR_i} * \frac{\partial FR_i}{\partial DP_j} * \frac{\partial DP_j}{\partial IV_j} \geq 1$$

Equation 10 Investment Performance Sensitivity

5 COMPLETE MODEL – MULTIPLE FR-DP RELATIONSHIPS

Assumption #1 in Section 4 is now retracted. Within the PDS, DP-Q111 (Training program) does not only affect FR-Q111 (Ensure that operator has knowledge of required tasks), but also FR-Q112 (Ensure that operator consistently performs tasks correctly) (see Figure 7). This is one example of the path dependent nature as defined by the PDS.

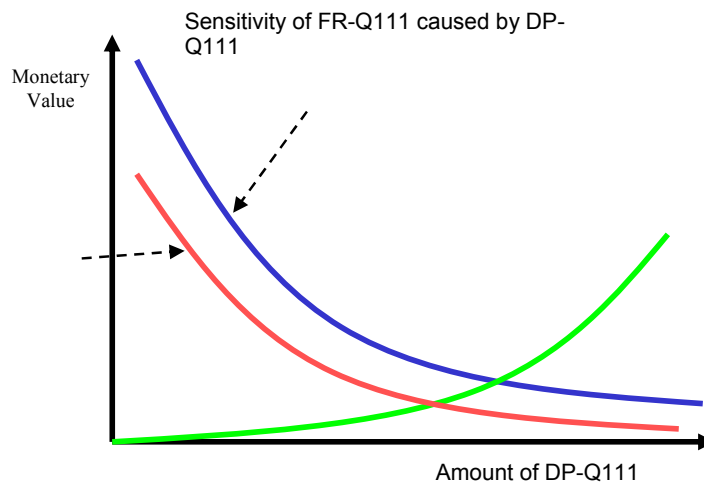


Figure 7 Sensitivity of Benefit to Investment – Multiple FR Case

The benefit from FR-Q112 is smaller than the benefit from FR-Q111, because FR-Q112 is mainly influenced by DP-Q112. The total benefit caused by further implementing a single DP is the sum of the individual benefits gained from better achievement of all path dependent FRs (see Figure 8).

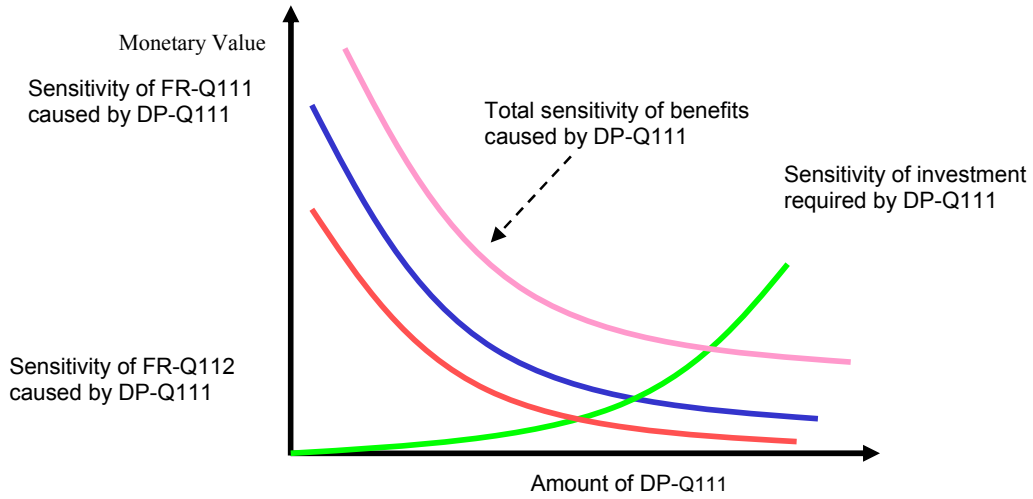


Figure 8 Total sensitivity of implementing DP-Q121

Mathematically, the allowable investment in DP-Q111 (from Figure 8) can be expressed as follows:

$$\frac{\partial IV(Q111)}{\partial DP(Q111)} \leq \frac{\partial BF(Q111)}{\partial FR(Q111)} * \frac{\partial FR(Q111)}{\partial DP(Q111)} + \frac{\partial BF(Q112)}{\partial FR(Q112)} * \frac{\partial FR(Q112)}{\partial DP(Q111)}$$

Equation 11 Investment Performance Sensitivity – Multi FR Case

This equation states that investment in DP(Q111) has a positive benefits to its path dependent FRs (FR(Q111) and FR(Q112)). Hence, investment in DP(Q111) should consider the benefits that arise in FR(Q111) and FR(Q112). For an investment in a DP that has path dependent FR benefits, the sum of the multiple benefits should be greater than the investment in the DP (see Equation 12).

$$IV(DP_j) \leq \sum_{i=1}^n BF(FR_i)$$

Equation 12 DP Investment Decision Equation

Equation 11 can be restated as:

$$1 \leq \frac{\partial BF(Q111)}{\partial FR(Q111)} * \frac{\partial FR(Q111)}{\partial DP(Q111)} * \frac{\partial DP(Q111)}{\partial IV(Q111)} + \frac{\partial BF(Q112)}{\partial FR(Q112)} * \frac{\partial FR(Q112)}{\partial DP(Q111)} * \frac{\partial DP(Q111)}{\partial IV(Q111)}$$

Equation 13 Investment Performance Sensitivity – Multi FR Case

Where:

$$R_{ij} = \frac{\partial BF_i}{\partial FR_i} * \frac{\partial FR_i}{\partial DP_j} * \frac{\partial DP_j}{\partial IV_j}$$

Equation 13 can now be expressed as:

$$1 \leq R_{BF(Q111),IV(Q111)} + R_{BF(Q112),IV(Q111)}$$

Equation 14 Investment Performance Sensitivity – Multi FR Case

Hence an investment should be considered as long as the sum of the sensitivities from all path dependent FRs is greater than one.

Or as a general expression:

$$1 \leq \sum_{i=1}^n R_{BF(FR_i),IV(DP_j)}$$

Equation 15 Investment Performance Sensitivity – Multi FR Case

Once the benefit sensitivities are summed for each DPj, improvement projects (DPs) can then be prioritized based on the summed benefit sensitivities [R_j] from the greatest to least with 1.0 serving as the lower limit for improvement projects. This will ensure the most effective allocation of constrained company resources.

6 ANALYSIS OF BENEFITS

To implement Equation 13 above, a clear understanding is required of calculating and evaluating the costs and the benefits from investing in a DP or a portfolio of DPs. Benefits can be evaluated over the lifecycle of the project. Within different organizations, the determination of the lifecycle will be case specific. However, once a credible lifecycle can be established, a variety of techniques can capture and measure the benefits of a system improvement project. Quantatively, most methods rely on discounted cashflows (DCF), with net present value (NPV) and real options valuation (ROV) being two examples.

7 IMPLEMENTATION

In practice, we recommend the following steps be undertaken:

1. System design evaluation to identify the health of the current system.
2. Valuation of FRs not fully achieved - estimate the potential benefits to be gained from each FR. If the benefit to an FR cannot be quantified, denote with a '+’.
3. DP contribution - understand the path dependency between valued FR to multiple DPs to derive the total contribution of a DP.

4. DP project valuation - calculate the investment required for the project to further implement a DP.
5. Undertake an NPV or ROV analysis of the expected benefits from achieving the FRs resulting from the investment in the DP.

8 CASE STUDY

Professor Cochran and his group worked with an aircraft manufacturing company facing challenging cost targets and having limited available resources. Management was seeking a scientific methodology to define their production system and guide their decision-making.

Data were not readily available on the cost incurred from not fully achieving the PDS requirements. Management estimated this cost to be about one-half of the current assembly (direct labor) time per aircraft. To determine the cost of not achieving the requirements, the three most recent aircraft to complete production were used as a baseline.

Accurately quantifying the impact of each PDS requirement not being met was nearly impossible, but from program metrics and data available, only the following PDS requirements and solutions could be **estimated**.

FR-111 'Design products that meeting program requirements'

DP-111 'Product Design Process'

FR-Q1 'Manufacture products within engineering requirements'

DP-Q1 'Elimination of assignable causes of variation'

(i.e. non-conformance work)

FR-P11 'Ensure availability of relevant production information'

DP-P11 'Capable and reliable information system'

(i.e. unavailable, late, incomplete, inadequate, or unclear work instructions)

FR-P12 'Ensure tools and supplies are available'

DP-P12 'Processes to ensure adequate supplies'

FR-P132 ‘Ensure availability of workers’

DP-P132 ‘Attendance policy enforcement’

(i.e. ‘labor loss’ - excessive, insufficient or untrained workforce compared to requirements)

FR-P15 ‘Ensure material availability even though fallout exists’

DP-P15 ‘Standard material replenishment approach’

(i.e. part shortages)

Figure 9 below shows the PDS with the quantified FR-DP pairs identified in red.

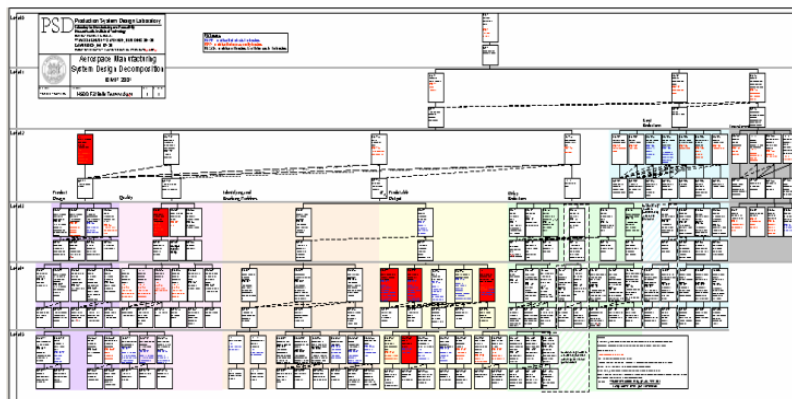


Figure 9 PDS Requirements Studied

Direct labor cost per plane was estimated for each of the above requirements while indirect (non-assembly) cost per plane was only estimated for FR111, FR-Q1, FR-P12 and FR-P15. Total program cost was calculated by summing the direct and indirect costs.

The graph in Figure 10 below displays the total labor hours per plane incurred from not fully achieving six PDS requirements (not account for path dependency).

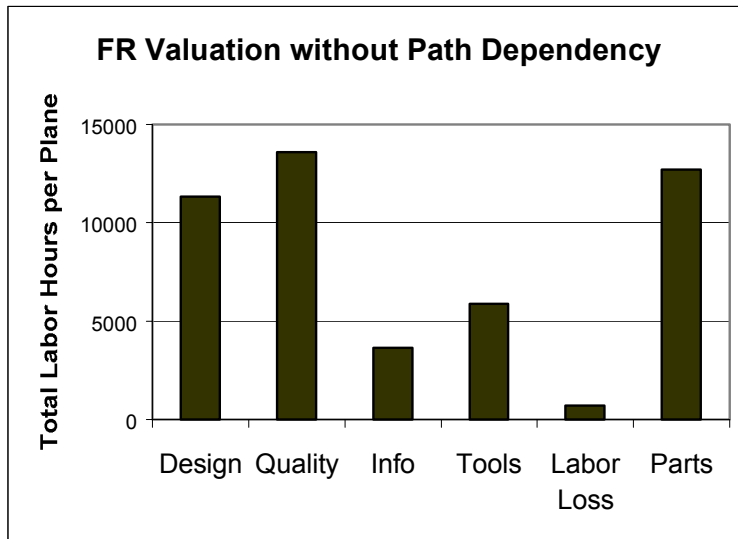


Figure 10 FR Valuation without Path Dependency

Because the PDS represents a path dependent design, investment in one DP will have a positive affect on multiple FRs. To more accurately estimate the allowable investment in each of the above DPs, the path dependency must be determined as shown in Equation 16 and Equation 17.

$$\begin{Bmatrix} FR-111 \\ FR-Q1 \\ FR-P11 \\ FR-P12 \\ FR-P132 \\ FR-P15 \end{Bmatrix} = \begin{bmatrix} X & - & - & - & - & - \\ X & X & - & - & - & - \\ X & X & X & - & - & - \\ X & - & X & X & - & - \\ - & - & - & - & X & - \\ X & X & X & - & - & X \end{bmatrix} * \begin{Bmatrix} DP-111 \\ DP-Q1 \\ DP-P11 \\ DP-P12 \\ DP-P132 \\ DP-P15 \end{Bmatrix}$$

Equation 16 Path Dependency of Studied PDS Requirements

Management estimated the magnitude of the design matrix elements (see Equation 17). For example, 90% of the cost of not fully achieving FR-Q1 ‘Manufacture products within engineering requirements’ was due to poor implementation of the direct DP, DP-Q1 ‘Manufacture products within engineering requirements,’ and the other 10% of the cost was incurred from not fully implementing DP-111 ‘Design products that meeting program requirements.’

$$\begin{Bmatrix} FR-111 \\ FR-Q1 \\ FR-P11 \\ FR-P12 \\ FR-P132 \\ FR-P15 \end{Bmatrix} = \begin{bmatrix} 1.0 & - & - & - & - & - \\ 0.1 & 0.9 & - & - & - & - \\ .03 & .03 & .94 & - & - & - \\ 0.8 & - & .05 & .15 & - & - \\ - & - & - & - & 1.0 & - \\ .01 & .02 & .01 & - & - & .96 \end{bmatrix} * \begin{Bmatrix} DP-111 \\ DP-Q1 \\ DP-P11 \\ DP-P12 \\ DP-P132 \\ DP-P15 \end{Bmatrix}$$

Equation 17 Path Dependency Contribution

The previous bar chart (Figure 10) is then modified according to the degree of the path dependency indicated in Equation 17 (see Figure 11). Consideration of the path dependency in the system design identifies and more accurately estimates the allowable investment in each of the DPs from the costs incurred from not fully achieving specific FRs.

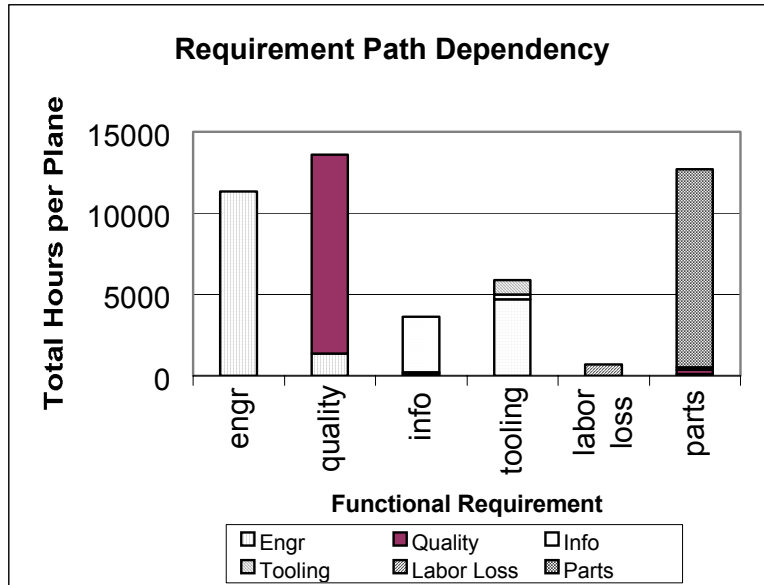


Figure 11 FR Valuation Based on Path Dependency

For example, as seen in Figure 11, not fully implementing the engineering DP (DP-111) affects not only the achievement of its direct FR (FR-111), but also has significant effects on achievement of quality (FR-Q1) and tooling (FR-P12) requirements. Figure 12 shows the summation of each DP's effect on their own direct FR and their path dependent FRs (i.e. depicted by summing the elements of each column in the design matrix [A]).

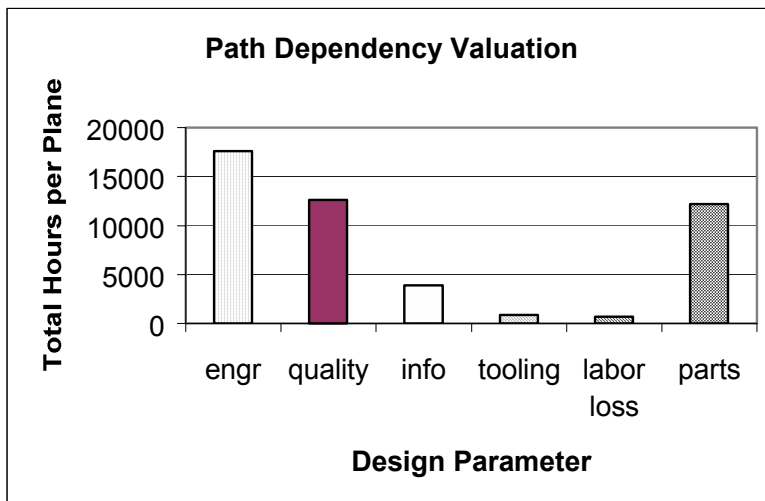


Figure 12 Allowable Investment in each DP

Accounting for path dependency yielded a more accurate estimate of the allowable investment in each of the DPs. For example, the allowable investment in engineering DP-111 increased 55% over DP-111's previous value as shown in Figure 9.

The PDS represents a system design in its entirety. **Every** FR must be achieved for the design to be complete. However, given limited resources, the knowledge of the path dependent relationships provides a scientific basis for the allocation of resources.

9 CONCLUSION

This paper develops a scientific approach based on the Product Delivery System to identify, evaluate and select continuous improvement projects, which have the greatest leverage to achieve system stability. The design matrix [A] defined in axiomatic design was used to derive a cost matrix [R]. The cost matrix enables comparison of potential improvement projects with respect to the path dependency as defined in the Product Delivery System. Hence, in the presence of constrained resources, improvement projects can now be evaluated and selected based on their potential leverage to achieve system stability requirements.

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