Design for control: A new perspective on process and product innovation

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Abstract

Product and process design have been examined from a multitude of perspectives: engineering, manufacturing, marketing, industrial design, as well as the integration of some or all of these perspectives. In turn, each perspective has led to approaches that are commonly known—design for manufacture (DFM), agile enterprise, concurrent engineering, value engineering, design for assembly (DFA), product data management (PDM), product life-cycle management (PLM), and many others. We propose a new perspective—design for control (DFC). DFC focuses on the carefully considered integration of new (or redesigned) parts/products into the control system structures that are used to plan and control the manufacture and assembly of products. We offer a formalization of DFC and the concept of “controllability” that facilitates development and maintenance of more efficient control systems.

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1. Introduction

The process by which organizations undertake product and process design has undergone a revolutionary change in the past several decades. Product design has been examined from a multitude of perspectives: engineering, manufacturing, marketing, industrial design, as well as the integration of some or all of these perspectives. This has produced considerable research on topics such as design for manufacture (DFM), agile manufacturing, concurrent engineering, value engineering, design for assembly (DFA), as well as many others. We propose a new perspective that is essential, given the current rapid movement toward information technology (IT) in the design and control of products—design for control (DFC). Although there are a number of important DFC issues that are common to DFM, DFA, etc., the emphasis on product and process innovation has been so pervasive in manufacturing that a direct focus on a design’s effect on “control systems” is imperative.

DFC focuses on the integration of new parts/products, or significant redesign of old parts/products, into the information system structures that are used to plan and control the manufacture and assembly of products. In manufacturing, these
systems commonly include material requirements planning, activity-tracking systems, quality control, product lifecycle planning, scheduling and dispatching systems, inventory management, and, more recently, ERP systems. The common thread that connects control systems and DFC is the emphasis on product and process innovation that has been recently observed in both the design process and the control system. For example, it is not unusual for new products to be designed with the goal of subcontracting some, or all, of the production activities associated with the product. DFC can provide guidelines for the economical use of control resources for the following: minimizing part counts, planning primary and alternative routings, monitoring and directing the product evolution, and consideration of the product structure level at which products and parts are subcontracted.

This paper proposes basic, conceptual tenets for analyzing this important issue. We purposefully use the term conceptual in that we identify a host of measurements that lend themselves to conceptualizing the terms “control” and “controllability”. Each of these measurements can subsequently be taken individually and studied in much greater detail. In this paper, we endeavor to simply introduce the concept of DFC in a unique and comprehensive manner. Thus, we consider our contribution to be the introduction of a basic conceptual framework from which future research can be extended.

This paper proposes a basic set of concepts for “control” as a distinct area of importance for management and for research. Certain aspects of control have been extensively researched. Examples are found in the literature of “quality control” and budget and cost accounting. But, in general, control has been an under-researched topic.

We can make clear what is involved by distinguishing between planning, operations, and control in the following manner: “Planning” is directed to effecting choices between alternative future courses of action. “Operations” consists of the actual commitment of resources, etc., to carry out the plans. “Control” is directed to evaluating and coordinating both the plans and the operations. This same distinction between “planning”, “operations”, and “control” is made by Charnes and Cooper (1961) in order to emphasize that linear programming applications are generally oriented toward planning.

An example is provided by the use of standard costs in accounting, where a “red variance” is associated with an undesirable operating performance, relative to the plan, and a “black variance” is associated with a performance better than planned. This is only a first step, however, since a black variance of sufficient magnitude can indicate where a planned performance may be improved, while a red variance of sufficient magnitude may point toward the possibility that aspects of the plan are not attainable.

This example is only indicative of the desirability of further research in the topic of control and its relation to integrating and improving both plans and operations. For concreteness, we shall focus on the process of new product introduction where these problems are particularly acute and significant, but our formulations will have greater generality than this, so we introduce measures that can, in turn, lead to other measures that conform to the conceptual framework that we provide. Thus, for clarity and ease of understanding, we shall generally focus on deterministic formulations that can be generalized to stochastic formulations like those in the Handbook on Data Envelopment Analysis (Cooper et al., 2004). Thus, in this sense our development is “conceptual” and the measures we develop should be understood accordingly. Finally, to lend concreteness to the development, we provide a series of figures in which key issues are identified and related to each other.

The development in the present paper proceeds as follows. In Section 2, we review relevant literature. This is followed by Section 3, in which we discuss issues in DFC. In Section 4, we introduce our definitions and develop our framework with appropriate examples. Finally, in Section 5 we discuss managerial implications and conclusions, which also include directions for future research.

2. Review of relevant literature

A great deal has been written about the managerial aspects of product design and its relationship to manufacturing management and IT. Rosenthal (1990) has identified six distinct areas of information processing important to the product design. In his taxonomy he identifies “tools and practices” that are organized into six categories—translation, focused information assembly, communication acceleration, productivity enhancement, analytical enhancement, and management control. Clark and Fujimoto (1989) point out that as the production competition gap among manufacturers has
narrowed, a shift to design and engineering has occurred. They note the complex and complementary interactions between manufacturing capability and design and vice versa. Often the focus of the managerial view of product design and manufacture is on speed of design (Stalk and Hout, 1990) and agile response to market demands and changes (Wheelwright and Clark, 1995; Womack et al., 1990).

DFM (Andreasen et al., 1983) and DFA (Bootroyd and Dewhurst, 1987) tend to be more engineering focused and employ specific rules and procedures for assessing the design of a part or product in terms of its cost and complexity. Designs receive a score by responding to a series of questions related to the way a product is assembled and the processes necessary to construct the product. One of the most prominent aspects of DFA and manufacture is part rationalization. This can occur by simply implementing the explicit reduction of the parts used to produce a product, or implicitly by considering the way in which a product is assembled—focused on the system of fasteners necessary to assemble a product. In either case, the goal is to reduce the cost of materials and assembly and manufacture time.

Recently, a new focus similar to DFM has become important, design for end of product life. In many situations, products are designed for long life cycles, while their parts tend to have shorter life cycles. This is the case with long-lived electronic products such as routers, communications equipment, and in many military hardware applications. Controlling the design of the products and the subsequent parts purchase decisions necessary to support product life has been discussed by Cattani (2005), Cattani and Souza (2003), and Bradley and Guerrero (2006). Insuring the durability of a product’s life can impose unanticipated costs that can lead to diminished profitability. Sood and Tellis (2005), Curran et al. (2007), and Solomon et al. (2000) provide insight on the level of design effort necessary to manage product end of life.

Motivation for research on DFC is seen in early work on new product development using component commonality (Gupta and Krishnan, 1999), and in sharing data within supply network (Loch and Terwiesch, 1998). DFC issues are also motivated by work in the organization context in concurrent product development (Krishnan and Ulrich, 2001). Some early framework on DFC was also presented by Bordoloi and Guerrero (2000).


In spite of the similarity of issues, little has been written regarding the explicit activity of DFC. There are incidental control benefits related to IT that are realized from DFM and DFA as mentioned earlier—in particular the reduction of part counts. Yet, the problems related to new product design and the attendant control issues that arise are real and complex, as evidenced by the development of product data management (PDM); Stark, 1992) and product life-cycle management (PLM); see IBM website) systems. PDM software systems attempt to manage engineering design information from the development of prototypes to production ready products. PDM software is integrated with software used by design groups (DeCastro and Hogerhuis, 1991) such as computer-aided design (CAD), engineering document management (EDM), document management, free-text databases, manufacturing requirements planning (MRP), and workflow/groupware (Wf). PLM is also often associated with PDM, but they place greater emphasis on process issues.

To fully appreciate the breadth of issues related to DFC, Section 3 presents a discussion of the control issues most affected by DFC. In Section 4 we suggest a detailed analytical structure, along with examples, to assess the benefits associated with DFC. Finally, in Section 5, we conclude with a summary of managerial implications and recommendations for future research in DFC.

3. Issues in DFC

In this section we outline some of the important control issues and activities associated with product
Our purpose is to identify control costs associated with these activities and the introduction of a new product design, i.e., costs that accrue to the control system, whether it is a sophisticated ERP system or a simple back-of-the-envelope system. To organize our analysis, we present the activities by categorizing them as either long term (persistent) or short term (infrequent).

Activities that lead to short-term costs are those that occur and are rapidly dispatched—for example, the initial Value Analysis or Value Engineering that is performed on a design, and subsequently used to aid in pricing, or the creation of a part or product code associated with a firm’s coding and classification system. Generally these activities take place once and the results are incorporated into the firm’s control system. Additionally, a cost is incurred and the cost is not likely to reoccur for this part or product; thus, it is a short-term cost. For an excellent and practical discussion of this topic, see Ibusuki and Kaminski (2007).

Activities related to long-term or persistent costs also occur in the new product design process. For example, managing the inventory of a new part is a design issue leading to a cost that is long term. The product will usually experience periodic cycle counting, warehousing management costs, and sustained safety stock costs, to mention a few, that are necessary once a product is designed and introduced into the control system. These costs will persist, and thus we refer to them as long term.

A summary of activities leading to long-term and short-term costs is provided in Fig. 1. The figure shows a broad and general set of possible issues. For a particular product design, the costs incurred will not necessarily include all the costs listed. Yet, it is reasonable to assume that many of the costs will be relevant to a product design. In Section 4 we present a more detailed discussion of the costs and introduce a formal definition of DFC, as well as our framework for analyzing the costs that result from the product and part design issues in Fig. 1.

4. Definitions

We now present our definitions of “control” and “controllability”. These definitions are based on the
concepts of “states”; thus, we start by introducing our definition of a “state” as follows:

**State**: a collection of capabilities that can be realized by activating a set of processes.

This definition of “state” is similar to that presented in Bordoloi et al. (1999), where it was used to define “flexibility” and “adaptability”. An example of a “state” might be a given machine setup, an existing workforce level, an existing bill of materials (BOM) for a product, an inventory level at a given time, or the current number of parts in a parts catalog. Each of these examples represents a current “operating state”. A change of state may be necessary when there are changes in external or internal conditions, such as market demand or a machine breakdown. Our conceptualization of control and controllability, which is given below, will utilize the above definition of a state.

Now, we define:

**Control**: an operating point in which certain performance measures (e.g. cost and time) are within desired amounts and directions.

**Controllability**: an ability to cope with change of states.

Our definition of control is comparable to Kohler’s Dictionary for Accountants (Kohler, 1983), in which Kohler defines control as given below:

**Control**: ability to influence behavior in desired amounts and directions, with the degree of conformance providing a measure of the state of control.

Controllability, as we define it, refers to a system’s capability to retain control over and withstand a change of states as a result of internal or external changes that allow a set of available inputs ($I$) to productively result in a set of desired outputs ($O$) while staying within certain target parameters such as cost ($S$) or time ($T$). Therefore, our definitions can be symbolically expressed (in terms of costs or time) as

Control: $C[I, O] \leq S$ or $C[I, O] \leq T$,

Controllability: $\Delta C[I_1, O_1], (I_2, O_2)] \leq S$

or $\Delta C[I_1, O_1], (I_2, O_2)] \leq T$,

where $I_1$, $O_1$ and $I_2$, $O_2$ are inputs and outputs of states 1 and 2, respectively.

We now introduce a numerical example to illustrate and elaborate further our definitions and conceptualization of control and controllability. We use this example at the “base case” and build upon it as we progress through the paper and formulate our future constructs.

4.1. Example

If a plant currently employs 100 full-time workers and is set to produce 1000 units a day, a *state of control* may be defined: (1) in terms of cost—if the scheduled production can be achieved within a target cost of $10,000. This is expressed as

$C[100, 1000] \leq 10,000$,

or (2) in terms of time—if the scheduled production is indeed achieved within a target time frame of 24 h. This can be expressed as

$C[100, 1000] \leq 24$ h.

A visualization of a simple state change is shown in Fig. 2.

Controllability, on the other hand, is characterized by the plant moving to 150 full-time workers for an expected production of 1500 units a day, i.e. a movement from the state of (100, 1000) to the state of (150, 1500). This *controllability* can be defined (1) in terms of cost—if the planned move can be made within the budget of $250,000, which can be expressed as

$\Delta C[(100, 1000), (150, 1500)] \leq 250,000$,

or (2) in terms of time—if the planned move can be made within a target time frame of 2 months, which can be expressed as

$\Delta C[(100, 1000), (150, 1500)] \leq 2$ months.

Fig. 2. An example of state change.
Next, we relate our framework with Kohler’s definition of control mentioned in the previous section. The state of control in Kohler’s definition is similar to our definition of state of control: \( C[I,O] \leq S \) or \( C[I,O] \leq T \). The overall definition of control by Kohler is comparable to our definition of “controllability”, where the desired amounts can be represented by \( \Delta C[I_1,O_1,I_2,O_2] \leq S \) or \( \Delta C[I_1,O_1,I_2,O_2] \leq T \) as proposed in our definition. As for the phrase desired directions in Kohler’s definition, our model already includes directional movement as leading to lower cost and reduced cycle time.

Our treatment of control and controllability in terms of cost can also be compared with the concept of target costing (Cooper and Regina, 1997). Just as target costing prescribes a cost-based design, our definitions of control and controllability prescribe setting target costs for stability (control) or movement (controllability).

While our definitions, using cost or time as performance measurement, can capture most situations, we agree that other measurements, besides cost and time, may also be used in a similar definition of control and controllability. As we develop various constructs later in this paper, we illustrate other types of measures.

4.2. Need for control

In this section, we identify the rationale for why we should focus on control and controllability. The need for control is generated by (1) the need to respond to pertinent changes in requirements or to changes in external or internal conditions, and (2) the need to manage different types of uncertainty. In Fig. 3 we identify four factors of uncertainty that generate the need for control. These four factors necessitate that some control system activity takes place. This adjustment or change to the control system will in turn produce costs. For example, an important customer (A) requests a change in a product purchased from a vendor (B) due to perceived demographic changes in its customer base. Then B undertakes a new product design that generates the need to perform the following activities: (1) a value analysis of the design, (2) creation of a new bill of materials, (3) incorporation of parts information into a parts master, PDM, and PLM systems, (4) determination of possible process routing of the product and its parts through the manufacturing facility, and (5) determination of possible vendors for outsourcing under conditions of constrained capacity.

Fig. 3 provides expanded details relating to four factors: (i) external, (ii) internal, (iii) supplier related, and (iv) customer related. The arrows indicate that some of these factors from different categories can interact with each other.

4.3. Measurement of controllability

Our goal, in this section, is to present a unified framework that makes it possible to identify and
position a wide variety of constructs for controllability. While it is also possible to develop measures for controllability that are continuous in nature, we offer a discrete framework that blends well with our state consideration, as defined earlier. This allows us to deal with state changes in response to requirements that generally occur at discrete points in time.

A manufacturing system usually operates under a set of external conditions or requirements such as market fluctuations and other possible environmental and economic changes. Such a system also has its own internal states that are usually best controlled by the system (Bordoloi, 1998, 1999).

In constructing the framework, we consider the following issues:

1. The concept of controllability should be meaningful when we compare two processes so that we can determine which process is more controllable than the other.
2. A need for considering controllability arises when either external requirements or internal conditions change or are anticipated to change.
3. Changes in external requirements, when significant, usually require responses by changes in the internal states within a process.
4. We evaluate a process by measuring the total cost for satisfying external requirements. It may be necessary to consider total profit as an alternative to total cost. Our definitions acknowledge this possibility, but here we focus on cost, and, in particular, the following important cost elements: (1) switching costs involved in changing from one state to another, (2) period or fixed costs of acquiring any capital equipment needed, and (3) the variable costs of operating the system. It is important to distinguish between switching and fixed (period) costs. For example, purchase of new machines as a part of planned capacity addition is a fixed cost, while enhancing machine capacities by changing machine setups to meet short-term demand fluctuations is a switching cost. Generally speaking, fixed costs are longer-term costs, while switching costs are shorter term.

We now introduce the following definitions for use in developing our mathematical formulations:

- \( r(t) \): requirement imposed for a process at time \( t \) (also \( r(t) \in R_p(t) \) for \( t \in [0, T] \));
- \( e(t) \): external state at time \( t \);
- \( S_p(t) \): set of the internal states that process \( p \) operates at time \( t \);
- \( s(t) \): internal state of process taken at time \( t \) (also \( s(t) \in S_p(t) \) for \( t \in [0, T] \));
- \( s^*(r(t)) \): internal state chosen to process requirement \( r(t) \) at time \( t \);
- \( W_p(s(t-1), s(t)) \): cost of switching from state \( s(t-1) \) to \( s(t) \) for process \( p \);
- \( F_p(S_p(t)) \): fixed cost of having the set of possible internal states \( S_p(t) \) in period \( t \) for process \( p \);
- \( V_p(s^*(t)) \): variable cost of processing requirement \( r(t) \) with state \( s^*(r(t)) \) in period \( t \) for process \( p \);
- \( C_p(s^*(t); s^*(t-1)) \): overall total cost of satisfying requirement \( r(t) \) with state \( s^* \) in period \( t \), given that it fulfilled requirement \( r(t-1) \) with state \( s^*(r(t-1)) \) in period “\( t-1 \)” for process \( p \).

Fig. 4 provides a graphic explanation of some of the above notation by establishing relationships between the internal state set and the requirement set. As the figure shows, for each element of the requirement set, there exists an optimal (chosen) internal state at a given time.

In continuation of our earlier example, the notation above can be used to extend the previous numerical example:

- \( R_p(t) \): a daily demand between 100 and 10,000 units; \([100,10,000]\);
- \( r(t) \): a chosen daily demand of 1000;
\( e(t) \) seasonality as an external state—e.g. Christmas season;
\( S_p(t) \) a set representing the number of full time workers between 50 and 500: \([50,500]\);
\( s(t) \) a possible workforce of 120 full time workers;
\( s^*(r(t)) \) a specific workforce level of 100 full time workers chosen for 1000 units;
\( W_p(s(t-1),s(t)) \) cost of switching from 100 workers to 150 workers;
\( F_p(S_p(t)) \) fixed cost of maintaining a possible labor pool of 50 to 500 workers;
\( V_p(s^*(t)) \) variable per unit cost of producing 1000 units with 100 workers.

Once different cost components are separately characterized, the overall total cost function in period "\( t \)" can be expressed as

\[
C_p(s^*(t); s^*(t-1)) = W_p(s^*(t-1), s^*(t)) + F_p(S_p(t)) + V_p(s^*(t)).
\]

This suggests that the overall total cost is the sum of the switching cost for moving from state \( s^*(t-1) \) to state \( s^*(t) \), the fixed cost of maintaining an internal state set \( S_p(t) \), and the variable cost for satisfying \( r(t) \), the requirement to be met at time \( t \). All three cost components have different roles to play in managerial decision making and in DFC.

We offer two measures for controllability while comparing processes. The first measure is the total cost that can be used to effect comparisons between processes. The second measure of controllability is the size of the internal state set \( S_p \)—i.e. \( S_q \) is a proper subset of the control elements in \( S_p \), or its derivative measurements. When we compare the internal state sets \( S_p \) and \( S_q \), for processes \( p \) and \( q \), respectively, we can say that process \( p \) is more controllable than process \( q \) when \( S_p \supseteq S_q \). This is so because we perceive that a larger set of internal states gives the manager a larger domain of options to achieve exactly what the manager tries to achieve—a proxy for control. Some of the derivatives of this measurement of size are service level, ease to bring about changes, time to make design changes, number of BOM levels, etc.

4.4. Representing some controllability measurements in our framework

We now demonstrate the comprehensive and unified nature of our framework by expressing some of the most commonly used measures for controllability, with respect to our framework. The framework is also sufficiently robust to allow measurement and evaluation of controllability in different manufacturing contexts.

Keeping in mind the different types of costs, the extent of controllability in processes can be compared in terms of one or more of the following measures:

1. The set of internal states, \( S_p \). This is internal to the system and it represents the process capability.
2. The requirement set, \( R_p \). This is external in nature and it may reflect market demand for a manufacturing company.
3. The cost comparison can be done in two ways: (1) the planned value (PV) of the total cost, as in a budget or standard cost, i.e. \( PV[C_p(s^*(t))] \), or (2) expected value (EV) of the total cost, i.e. \( E[C_p(s^*(t)) ; e(t)] \). The PV measure would keep the analysis deterministic, while analysis of the underlying uncertainty may make it necessary to utilize the EV. We will emphasize the deterministic formulation in terms of PV in this paper, while noting the possibility of the probabilistic formulation if and when the need arises.
4. The difference in the PV or the EV of total cost between times "\( t+1 \)" and "\( t \)"—i.e., \( PV[C_p(t+1)] - E[C_p(t)] \) or \( E[C_p(t+1)] - E[C_p(t)] \). This deals with events occurring at a discrete instant in time.
5. Certain specific measurements for controllability (derivatives of size), that offer clearer meaning to the "control" aspect. Examples include BOM complexity, time to redesign, forecast accuracy, etc. This will be explained in greater detail in later sections.

We now select some common measures for control and controllability in line with Fig. 1 and show how they can be represented in our framework. We will take the platform of the same example that we illustrated earlier, and walk through many control and controllability measures to demonstrate how our framework can represent each measure.

4.5. Design process

4.5.1. Value analysis (measured in component commonality/modularity)

Let \( z \) denote an acceptable level of fixed cost for maintaining the parts/components for the entire
product range. \( S_p \) is the set of possible internal states (e.g. product variety) that satisfy \( F_p(S_p(t)) \leq x \). Then, process \( p \) has higher controllability than process \( q \) if \( S_p \supseteq S_q \).

For example, for an acceptable level of fixed cost for maintaining the parts/components for the entire product range of, say, $100,000, if process \( p \) has a product range of \([10, 100]\) compared to process \( q \) of \([20, 80]\), we say that process \( p \) has a higher controllability than process \( q \).

4.5.2. Design/redesign efficiency (measured in time to design/redesign)

Let \( x \) denote an acceptable level of fixed cost for the design/redesign. \( T_p \) is the time to design/redesign in process \( p \) that satisfies \( F_p(T_p(t)) \leq x \) for \( S_p \), which represents the set of internal states for the design/redesign system (e.g. number of engineers). Then, process \( p \) has higher controllability than process \( q \) if \( T_p < T_q \).

For example, for an acceptable level of fixed cost for the design/redesign of, say, $100,000, if process \( p \) can complete the required redesign in 1 month, as compared to process \( q \) in 2 months, we say that process \( p \) has a higher controllability than process \( q \).

4.5.3. DFM/assembly (measured in ease of manufacturing/assembly in terms of changes in design process)

Let \( r(t) \) be the requirement in terms of volume of design changes in time \( t \). For example, 50 design changes are needed within the month.

\[ PV_{r(t)}[C_p(s^*(t); s^*(t-1))] \] is the PV of the total cost for DFM/A. For example, 100 design engineers are needed this month to make the 50 design changes, while the last month’s usage was 90 design engineers; e.g. \( PV_{50}[C_p(100, 90)] = $10,000 \).

We say, process \( p \) has higher controllability than process \( q \) if

\[ PV_{r(t+1)}[C_p(s^*(t+1); s^*(t))] - PV_{r(t)}[C_p(s^*(t); s^*(t-1))] < PV_{r(t+1)}[C_q(s^*(t+1); s^*(t))] - PV_{r(t)}[C_q(s^*(t); s^*(t-1))]. \]

For example, if the next month’s design change is 60, for which 120 design engineers will be needed, and the cost comparison is as follows:

\[ PV_{60}[C_p(120, 100)] - PV_{50}[C_p(100, 90)] < PV_{60}[C_q(120, 100)] - PV_{50}[C_q(100, 90)], \]

then, process \( p \) has higher controllability than process \( q \).

4.5.4. Process selection and routing (measured in flexibility in routing)

Let \( x \) denote an acceptable level of fixed cost for maintaining a set of different routes to make the products. \( S_p \) is the set of possible internal states (possible routes) that satisfy \( F_p(S_p(t)) \leq x \) for \( S_p \).

Then process \( p \) has higher controllability than process \( q \) if \( S_p \supseteq S_q \).

For example, for an acceptable level of fixed cost for maintaining a set of different routes to make the products of, say, $100,000, if process contains 20 possible routes to produce the required product range, as compared to 15 routes for process \( q \), we say that process \( p \) has a higher controllability than process \( q \).

4.6. Inventory control

4.6.1. Inventory policy (measured in cycle/safety stock level)

Let \( r(t) \) be the requirement in terms of parts in demand in time “\( r \)”. For example, the monthly demand is 1000 parts. \( PV_{r(t)}[C_p(s^*(t); s^*(t-1))] \) is the PV of the total cost on inventory stock.

Process \( p \) has higher controllability than process \( q \) if

\[ PV_{r(t)}[C_p(s^*(t); s^*(t-1))] < PV_{r(t)}[C_q(s^*(t); s^*(t-1))]. \]

For example, if the PV of the total cost on 1000 parts for process \( p \) is $100,000, and that of process \( q \) is $150,000, i.e.

\[ PV_{1000}[C_p(s^*(t); s^*(t-1))] = $100,000 \]

and

\[ PV_{1000}[C_q(s^*(t); s^*(t-1))] = $150,000, \]

then, process \( p \) has higher controllability than process \( q \).

4.6.2. Demand management (measured in forecasting effectiveness using MAD)

We offer two possible measurements of this using our framework:

(i) Compare processes in terms of forecasting accuracy/reliability. Let \( x \) denote an acceptable level of fixed cost for the forecasting system.

MAD\(_p\) is the mean absolute deviation (MAD) for process \( p \) that satisfies \( F_p(S_p(t)) \leq x \) for \( S_p \), which represents the set of internal states for the forecasting system.
Then, in our terms, process $p$ has higher controllability than process $q$ if $\text{MAD}_p < \bigcap \text{MAD}_q$.

(ii) Compare processes in terms of the total cost for a target MAD level. Let $s^*(t)$ denote the desired target MAD level at time period $t$ for the forecasting system.

Then process $p$ has higher controllability than process $q$ if $C_p(s^*(t)) < C_q(s^*(t))$.

4.7. Production control

4.7.1. Issue of shop papers (measured in process commonality)

Let $\alpha$ denote an acceptable level of fixed cost for process control in shop floor. $\text{SP}_p$ is the volume of shop paper for process $p$ that satisfies $F_p(S_p) \leq \alpha$ for $S_p$, which represents the set of internal states (e.g. number and type of machines) for process control on the shop floor. Then, process $p$ has higher controllability than process $q$ if $\text{SP}_p < \text{SP}_q$.

This measure compares process commonality. For example, for an acceptable level of fixed cost for process control in shop floor of, say, $100,000$, if process $p$ has 10 types of machines (for process commonality), as compared to 15 for process $q$, we say that process $p$ has a higher controllability than process $q$.

4.7.2. Capacity control (measured in workforce/resource planning)

This may be captured in terms of allowance for capacity changes to take care of anticipated changes in demand. One method to formulate this will be in a chance-constrained programming formulation as in

$$\Pr(C_t \geq d_t) \geq \alpha,$$

where $C_t$ represents capacity in time $t$ and $d_t$ is a random variable for demand in time $t$, with the constraint to be satisfied with probability $\alpha$. Hence, $1 - \alpha$ is the risk of demand exceeding the capacity of $C_t$.

For example, for a certain demand, say 1500 parts in time $t$, if capacity $C_t$ results in meeting demand with a probability of 98% (risk of 2%) in process $p$ as against a probability of 95% (risk of 5%) in process $q$, we say that process $p$ has a higher controllability than process $q$.

We note that the chance-constrained programming formulation covers all of the points (and only those points) exceeding $C_t$. Hence it completely covers all possibilities of the risk of exceeding capacity that need to be considered. Thus, this is a better measure of risk than the commonly used variance measure because the latter covers only deviations among the value of the central tendency measure $C_t$. Charnes et al. (1958) elaborate this in the originating article for chance-constrained programming, which contains an actual application in which probabilistic coverage of capacity constraints is included.

4.8. Post production control

4.8.1. Field parts management (measured in $\text{PV}$ of cost to achieve a desired target service level)

Let $r(t)$ be the requirement in terms of demand volume for field parts in time "$t$". For example, the monthly demand is 1000 field parts. $\text{PV}_{t}(C_p(s^*(t); s^*(t - 1)))$ is the PV of the total cost for field parts management to meet a desired service level of $\beta$.

Process $p$ has higher controllability than process $q$ if

$$\text{PV}_{t}(C_p(s^*(t); s^*(t - 1))) < \text{PV}_{t}(C_q(s^*(t); s^*(t - 1))).$$

This measure compares the PV of the cost in meeting a desired service level (e.g. percentage of times the field part supply is met). For example, if the PV of the total cost on 1000 parts for process $p$ is $100,000$, and that of process $q$ is $150,000$, i.e.

$$\text{PV}_{1000}(C_p(s^*(t); s^*(t - 1))) = 100,000$$

and

$$\text{PV}_{1000}(C_q(s^*(t); s^*(t - 1))) = 150,000,$$

then, process $p$ has higher controllability than process $q$.

4.8.2. Spares support (measured in terms of service level for customer support)

Let $\alpha$ denote an acceptable level of fixed cost for maintaining the spares support system. $\text{SL}_p$ is the service level for process $p$ that satisfies $F_p(S_p(t)) \leq \alpha$ for $S_p$, which represents the set of internal states for the spares support system (e.g. inventory of spares).

Then, process $p$ has higher controllability than process $q$ if $\text{SL}_p > \text{SL}_q$.

This measure actually compares service levels in terms of, say, percentage of times spares were available when the customer needed them. For example, for an acceptable level of fixed cost for maintaining the spares support system of, say,
$100,000, if process \( p \) can achieve a service level of 98%, as compared to 95% for process \( q \), we say that process \( p \) has a higher controllability than process \( q \).

4.8.3. Training (measured in knowledge stock)

Let \( x \) denote an acceptable level of fixed cost spent on training. \( K_p \) is the knowledge stock (skill acquired) in process \( p \) that satisfies \( F_p(S_p(t)) \leq x \) for \( S_p \), which represents the set of internal states (e.g., types and methods of training) for the training system.

Then process \( p \) has higher controllability than process \( q \) if \( K_p > K_q \).

This measure compares the degree of training depth. For example, for an acceptable level of fixed cost spent on training of, say, $500,000, if process \( p \) can train up to Grade 10, as opposed to up to Grade 8 for process \( q \), we say that process \( p \) has a higher controllability than process \( q \).

5. Managerial implications and conclusions

The design or redesign of a product or process has far-reaching consequences for the systems used to control the manufacturing process and its related activities. Particularly, the costs associated with these activities are often difficult to track and trace through traditional accounting. As we have discussed, numerous attempts have been made to capture some of these costs or related measures. But most authors take a piece-meal approach, thus a comprehensive system that incorporates all measures in a single platform has heretofore been neglected. Therefore, we have identified in Section 4 measures that provide managers with a formal structure for making decisions relating to efficient use of their control system. These measures could also be used to aid in the selection or design of a control system.

Structure and formality in dealing with the product design decision is essential given that an infrastructure change to the control system is often extremely costly and difficult to perform. This is particularly true with general-purpose systems such as those we classify as ERP systems. Often it is more likely (and less costly) that we can change our processes and procedures than change the infrastructure of the control system.

In the business experience of the authors, we have encountered companies that have information on literally millions of parts stored in parts masters or parts catalogs in their MRP systems—in one case a firm has in excess of four million active parts. Not surprisingly, manufacturing companies can become lost in the midst of this mountain of information, and are often unable to synthesize this available information in an economical way. There are patches that can be applied to remedy the enormous problem of tracking the millions of transactions related to these parts, such as PDM. Yet, a more prudent approach to this problem is to carefully, and formally, consider the implications of new product design prior to execution.

Besides offering numerous benefits for planning and executing design decisions, DFC provides us with a formal methodology to examine the following:

- Comparison of competing designs—a head-to-head comparison of the costs and effects of one design versus another.
- Time flexibility—use of “postponement” techniques (delay of certain design features as late as possible (Lee and Billington, 1992)).
- Discipline in design—DFM and DFA have been well integrated into design processes, now DFC can be utilized to consider the effect on control.

Our goal in this paper has been to provide a conceptual foundation for considering the effect of product and process design in settings where product and process innovation is of utmost importance. Additionally, we provide a comprehensive and unique foundation to express the effect of design issues on control within a common framework. We believe that our formalization of these design issues is comprehensive and accommodates other partial formalizations in the literature. There is obviously much work yet to be done to further the formalization and execution of individual measures, and we hope that this paper provides a path to that work. For example, this paper discusses only a limited extent of stochastic formulation. A much broader discussion on stochastic formulation may be necessary for the appropriate applications. For example, our formulation with \( P+ \) can be extended to capture \( E+ \) if the situation demands allowances for deviations from planned costs. Also, we have offered only the basic chance-constrained formulation and its corresponding risk considerations. A much detailed risk analysis can be performed if desired.
Similarly, this paper does not develop any optimization models. But we hope that our conceptualization of control and controllability paves the path for possible optimization models in the future.

Extensions can be made to parameters other than cost and time. For example, if inter-firm comparison is necessary, a useful parameter would be market share, providing a marketing perspective.

Finally, we hope that this paper will bring to light the importance of control in manufacturing systems, particularly as it relates to design of products and processes. We do so with a special emphasis on cost comparison that is generally missing in the current literature. Additionally, since control has been overshadowed by other design-related concepts such as flexibility, complexity, variety, and quality, we feel the need to recognize formally the costs associated with decisions relating to control.

Our formalization of controllability is comprehensive, unified, and is provided in more complete detail than that attempted for comparable issues such as flexibility and quality in the literature. We also predict that, with the advancement of IT, the need and significance of controllability will achieve parity with other design issues that are currently in practice. Finally, we strongly believe that future innovations in product and process design are only partially complete if done so without the appropriate consideration of control and controllability.

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