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Modeling and optimization of product design and portfolio management interface

Beverly V. Smith, Marianthi G. Ierapepritou *

Rutgers University, Department of Chemical and Biochemical Engineering, Piscataway, NJ 08854, United States

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ABSTRACT

The paper presents modeling and analysis of product design and product portfolio management (PD–PM) domains interaction using an integrated simulation–optimization model. To represent the interactions, the product design phase is modeled as a discrete-scenario static system. The goal of this work is to develop a decision support framework that relies on product design–product portfolio management integration in order to aid product design planning and design execution. We utilize dependency matrix approach to illustrate domain relation between the product design and product portfolio management domains, and to facilitate their integration. Hence, the process integration model utilizes iterative effects, and their attendant processing duration and costs, to pattern domain interaction. An industrial case study is used to illustrate the application and utility of the proposed approach.

1. Introduction

The product development process can be characterized by related sets of technological and business decisions that are made in situ. The linking of these two sets of decisions facilitates complete and accurate project (product) valuation by ensuring consideration of both commercial and technical requirements (Georgiopoulos, Jonsson, & Papalambros, 2005; Michalek, Feinberg, & Papalambros, 2005). Furthermore, product developers have come to acknowledge that greater coordination and integration of specialized capabilities yield measurable improvement in product development cycle time and development cost (Bode, Schomacker, Hungerbuhler, & McRae, 2007; Krishnan, 1998; Sogomonian & C.S., 1993). However, while acknowledging the need for technological and business integration, researchers have also admitted that there is a real challenge in formalizing the relationship between the disciplines (Georgiopoulos et al., 2005; Michalek et al., 2005) and quantifying its impact. According to Michalek et al. (2005) the reasons for this absence of a coordinated framework can be traced to historical developments and perceptions of disciplinary boundaries. Nevertheless, a number of models have been proposed in the academic literature that seeks to quantify the interdependence of investment decisions and engineering performance decisions via analytical evaluation (Georgiopoulos, 2003; Georgiopoulos, Fellini, Sasena, & Papalambros, 2002; Georgiopoulos et al., 2005; Michalek et al., 2005). Such models, in forging the linkage of the two disciplines may lead to improved portfolio decisions; however it may not address issues associated with inefficient coordination, therefore yielding less than optimal portfolio decisions.

Recently Ng (2004) offered a hierarchical framework that relied on distinctions in decisions length and time scales within a chemical enterprise. Such layered distinction provides the basis for linking business decision making to product and process design; wherein regions of overlap indicate the presence of interaction between levels of decision making. Moreover, the number of iterations between the various levels is minimized when decisions are made in the order of decreasing length and time scales. In recognizing the influence of dynamic market conditions and unpredictable changes in business conditions, this novel approach ignores the random nature of decision making in response to these uncertain conditions. In this study we assess interaction between technical and business domains based on recognized dependence relationship, while accounting for uncertainties that influence interactions.

With a growing intensity in global market competition, firms within the chemical and related industries are forced to develop products at a rapid pace, while minimizing development costs and ensuring product quality (Smith & Ierapepritou, 2009). Faced with such stark reality, firms must optimize their development process by eliminating inefficient practices such as wasteful iterations and ineffective communication during the product development process (Cho & Eppinger, 2005; Clark & Fujimoto, 1991; Meier, Yassine, & Browning, 2007; Ulrich & Eppinger, 2000; Wang & Lin, 2009). Such industry imperative warrants the application of a wide range of streamlining strategies; including efficient coordination across disciplinary boundaries. Other practices aimed at reducing product development cycle time include activity crashing, overlap-

* Corresponding author.
E-mail address: marianth@soemail.rutgers.edu (M.G. Ierapepritou).

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Nomenclature

a_k	kth product design project
B_k	product design budget constant for project k
$C_k(x)$	basic product design cost function for project k
D	product design domain symbol
E	expectation operator
$F(y, \omega)$	expected portfolio performance obtained from the simulated outcome
$\hat{F}(y, \omega)$	approximated product portfolio performance measure
$f(y_k) \geq 0$	constraint for planned iteration between product design i and product portfolio elements j for project k
γ_k	mean resource cost rate for product k
$G(z_k, z'_k)$	budget cost function for project k
Γ_{ijk}	mean cost associated with matrix cell n_{ijk} of project k
I	set of product design decision elements
J	set of product portfolio decision elements
K	set of product design projects in the product design portfolio
λ_k	function for the number of iterations between the product design portfolio domains for project k
n_{ij}	binary value indicating dependence between DMM element i and j
n_{ijk}	binary value indicating dependence between DMM element i and j for project k
N	total count indicating dependence for all projects within the portfolio
M	total number of design equality constraints
p	product design material component
R	total number of product design inequality constraints
S	vector of portfolio scenario
t	design time decision variable
T_k	time horizon for project k
x	design material decision variable
ω	random variable vector that represents the number of iterations
y	binary decision vector
y_{ijk}	binary variable indicating the existence of dependence and iteration between decision elements i and j of project k
y_k	binary decision variable indicating the existence of dependence and iteration
z_k	iterative product design cost function for product k
z'_k	basic design cost function for product k
$Z(y, \omega)$	random vector that represents the simulation outcome

ping of activities and concurrent exploration of design alternatives (Graves, 1989). A search of the literature revealed a disproportionate focus on product design activities as targets for streamlining the product development process (Langerak & Hultink, 2008; Langerak, Hultink, & Griffin, 2008; Millson, Raj, & Wilemon, 1992; Steward, 1981). Steward (1981) introduced the problem of managing product design activities by analyzing the flow of information embedded in the design of a given product. In subsequent studies, Novak and Eppinger (2001) introduced the design structure matrices (DSM) to enhance the capability for evaluating product design activities.

According to Roemer and Ahmadi (2004), the management of the development process may require coordination between design activities with complex information dependencies. However, such coordination must extend beyond the product design domain in order to realize maximum efficiency accompanying product development execution. Hence, in this study we have expanded the field for product design coordination beyond intra-design activities and explore opportunities for product development performance improvement by modeling the integration of product design domain and the project selection aspect of the product portfolio management domain, as shown in Fig. 1.

Given the decision dependence relationship between the two domains, the principal question now becomes how to obtain optimal interaction in an effort to avoid unnecessary project delays and cost while ensuring realistic resource allocations. Our goal in this study is to minimize the number of iterations between the domains by applying relevant streamlining policies and determining the optimal scenario for domains integration for a given set of projects that constitutes the design phase product portfolio.

The paper is organized as follows: in the next section we review the approach for product design–product portfolio management integration. Section 3 outlines the domain dependencies that formed the basis of our integrative approach and has contributed to the development of the proposed computational framework. The problem description and model formulation is presented in Section 4, followed by an industrial case study to illustrate the proposed framework in Section 5, and concluding remarks in Section 6.

2. Product design-product portfolio management (PD–PM) integration

Process modeling, simulation and optimization techniques have been widely deployed to address product development performance concerns, such as the pressing need for cycle time reduction (Schmidt & Grossmann, 1996; Schmidt, Grossmann, & Blau, 1998; Subramanian, Pekny, & Reklaitis, 2000; Varma, Pekny, Blau, & Reklaitis, 2008). Schmidt and Grossmann (1996) and Schmidt et al. (1998) are recognized as early contributors who have formalized the optimization of new product development process using mixed integer programming.

However, according to Wynn, Eckert, and Clarkson (2007), the modeling of product development process offers unique challenges due in part to the uncertainty that characterizes the design process – a critical stage within product development. Among the factors contributing to the difficulty encountered in modeling product design process, Wang and Lin (2009) cited the dependence of the process outcome on "the technical decisions that are made by examining the design *in situ*". Furthermore, in contrasting manufacturing process to product development, they have asserted that the product development process is one of creativity and discovery and therefore lends itself to trial and error. The creativity is further warranted by uncertainties due to technological risks (Varma et al., 2008) shifting customer requirements and changing business conditions. In part, such factors account for the iterative nature of the product development process evidenced by design tasks rework and repeated resource allocation. According to Chen and Lin (2003) difficulties encountered in designing complex products does not simply arise from their engineering complexity, but also stem from the organizational sophistication necessary to manage the design process. Hence, this study examines the interaction between aspects of product design and product portfolio management process with an aim to resolve some of these difficulties created by wastes and inefficiency.

2.1. Product design and portfolio decisions

The term product design refers to the detailed development that yields specification of design variables and parameters. Hence,