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Development of a fuzzy goal programming model for optimization of lead time and cost in an overlapped product development project using a Gaussian Adaptive Particle Swarm Optimization-based approach

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ABSTRACT

The aim of this paper is to present a model-based methodology to estimate the optimal amount of overlapping and communication policy with a view to minimizing product development lead time and cost. In the first step of methodology, the underlying two factors are considered in order to formulate mathematically a multi-objective function for a complete product development project. To add these objectives, incommensurate in nature, a fuzzy goal programming-based approach is adopted as the second step. In order to attain the optimal solution of formulated objective function, this paper introduces a novel approach, "Gaussian Adaptive Particle Swarm Optimization" (GA-PSO), which is embedded with two beneficial attributes: (1) Gaussian probability distribution, and (2) Time-Varying Acceleration Coefficients strategy. An illustrative hypothetical example of mobile phones is detailed to demonstrate the proposed model-based methodology. Experiments are performed on an underlying example, and computational results are reported to support the efficacy of the proposed model.

1. Introduction

The present industrial market is witnessing a faster "*time-to-market*" while maintaining or enhancing its product quality scenario for continuously shortening life-cycle products. This is because products that are launched earlier capture the whole market and so achieve phenomenal success (Kotler, 2003). Among the many tools that accelerate the product development process, concurrent engineering (overlapping of stages) has evolved as the most prominent option for efficient and effective product development (Smith and Reinertsen, 1998). The significance of this strategy has been reinforced more by its successful implementation in developing airplanes (Sabbagh, 1996) and software (Cusumano and Selby, 1995). Overlapping involves the concurrent execution of two successive stages and allows the second stage to begin before the first stage is finished. Here, the first stage is called upstream and the second stage downstream. Overlapping facilitates the two leading purposes of any organization, i.e., lead-time compression and quality control. The first objective is achieved by parallel execution of upstream and downstream stages while the latter results from the release of rudimentary information from upstream. In this way, engineers can step ahead to identify any mistakes and then can enact preventive action rather than letting the problem accumulate and so be forced to revise the situation extensively (Cantamessa and Villa, 2000). This is contrary to the traditional sequential approach, in which commencement of the next stage occurs only when the previous stage has ended completely and has transferred the final information.

Serious risks, however, are associated with the transfer of rudimentary information because of its inherent uncertainty. Therefore, in order to reduce any associated risks, cross-functional teams communicate through a number of meetings known as pre-communication before the project's start. For the purpose of uncertainty reduction, a team of overlapped groups update information regularly until the upstream stage is finished. This information is exchanged through the active participation of teams that require additional time and cost. An exchange of updated information through sporadically held meetings is termed as the communication policy, and it plays a vital role in reducing the uncertainty inherent in rudimentary information (Loch and Terwiesch, 1998). This continuous refinement of available information at the upstream stage, from rudimentary to final before the complete execution of the stage, is termed as "*information evolution*" and leads to modifications (Krishnan, 1996). Thus, the upstream stage faces modifications after each meeting and

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Nomenclature

N	stages in product development project.
N_i	nominal days for *i*th stage
T_{US}	nominal duration of upstream stage
T_{DS}	nominal duration for downstream stage
T_I	time for maiden information transformation to downstream stage from upstream
T_m	lower bound on T_I
T_{seq}	time completion time for two successive stages in sequential pattern.
T_{conc}	time completion time for two successive stages in overlapping pattern.
T_{RET}	rework time
T_{COT}	communication time
T_{NO}	non-overlapped stages time
C_ψ	pre-communication cost
C_{AWC}	actual working cost
C_{REC}	rework cost
C_{COT}	communication cost
C_{NO}	non-overlapped stages cost
o_group	number of overlapped group of stages
no	number of non-overlapped stages
Δ_{iter}	time interval between two information bursts for a group of overlapped stages
T_{iter}	time for next information burst after the previous one
T_{Mag}	the goal of product development lead-time decided by management group.
C_{Mag}	the goal of product development cost decided by management group
λ_t	profit due early launching of product
λ_r	rework cost or unit time cost of rework
λ_β	set-up time for communication per meeting
η	set-up cost per meeting
r	rework rate at downstream stage
$\pi_k(T^{US})$	non-negative average rate of modifications
π_0	level of technical uncertainty at beginning of project in absence of planning
B	the organization's ability to reduce uncertainty during pre-communication
Δ_n	downstream stage progress at any time t
p	percentage of downstream work affected by each modification
δ	number of modifications at any time t
(T_I+T_{DS})	actual working time for actual working cost
T_{Max}	maximum amount of overlapping
T_{Min}	minimum amount of overlapping

Decision variables

Ψ	pre-communication time
μ	amount of overlapping for each group
n^*	maximum number of information burst in a group of overlapped stages.
CP	communication policy for each group of overlapped stages

provides these changes to the downstream stage, which started earlier on the basis of rudimentary information. This may result in reduced product development lead time, but at a trivial amount of additional cost for rework (Terwiesch and Loch, 1999; Roemer et al., 2000).

After receiving the updated input information, the downstream stage generates the required information and accommodates all changes through rework. If the upstream stage transfers the individual change as soon as it appears, the downstream stage will have to iterate each time to accommodate changes. This will lead to gigantic additional time at a smaller rework cost. On the other hand, if updated information is not transformed frequently, then this situation may lead to developing a product with poor quality with less communication time, at a higher cost for rework. As a result, it is necessary to investigate the cost-time trade-offs involved in overlapped product development process, so as to enhance performance. Otherwise, its application may result in a higher number of downstream iterations, i.e., rework, thereby augmenting both time and cost (Lin et al., 2010). For this reason, the amount of pre-communication, along with the communication policy and the extent of overlapping stages, should be decided meticulously, so as to achieve the desired goals.

This paper first presents an analytical model to estimate the optimal value of decision variables (i.e., number of pre-communication meetings, amount of overlapping of each group of overlapped stages, and communication policy for each group of overlapped stages involved in a complete project) with an aim to minimize the lead time and cost. The aforesaid decision variables are estimated by addressing the issue of target cost and time. Owing to the significance of objectives (i.e., product development lead time and product development cost) the underlying problem is considered as an example of a multi-objective optimization problem. The incommensurate nature of these objectives constrains their explicit summation. Therefore, the fuzzy goal programming concept, because of its flexibility in the modeling of multi-objective problems, is introduced to add these objectives. Third, a novel meta-heuristic optimization approach, "Gaussian Adaptive Particle Swarm Optimization (GA-PSO)," is proposed to find the optimal/near-optimal solution of the problem at hand.

In this meta-heuristic approach, random numbers are not generated by applying the uniform distribution function. Instead, the Gaussian probability distribution function is applied. This offers the advantage of enhanced search capability while maintaining adequate exploitation capability. Two other variants have been applied that employ Cauchy distribution and Random numbers (RNs) generators, and the results are thoroughly analyzed to draw useful insights. Additionally, a novel parameter automation strategy is applied that includes time-varying acceleration coefficients (TVACs) strategy apart from the time-varying inertia weight (TVIW). The advantage of TVACs is to make the algorithm more robust while exploring the whole search area in the initial phase and to approach nearer-optimal solution in a later phase.

Depending on the newness of the company and market opportunities, McDermott (1999) and Hauser et al. (2006) defined two types of innovation in product development (namely, incremental and radical). Incremental innovation refers to the inclusion of some new features or to the improvement of existing features, whereas radical innovation refers to the introduction of a product with a set of original features. Most radical innovations are generally incremental types of innovations. This is due to the fact that major portion of so-called *newly launched products* is virtually build by strategically exploiting the knowledge, technologies, processes and resources of already existing products (Hauser et al., 2006). It is very unusual for an organization to introduce a product to the market that does not have some common features or technology with contemporary products.