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Hybrid particle swarm optimization with mutation for optimizing industrial product lines: An application to a mixed solution space considering both discrete and continuous design variables

Stelios Tsafarakis [a,*], Charalampos Saridakis [b,1], George Baltas [c,2], Nikolaos Matsatsinis [d,3]

[a] Technical University of Crete, Department of Production Engineering and Management, Agiou Titou square, Chania 73132 Greece
[b] University of Leeds, Leeds University Business School, Maurice Keyworth Building, Leeds LS2 9JT UK
[c] Athens University of Economics and Business, Department of Marketing and Communication, 76 Patission Avenue, Athens 10434 Greece
[d] Technical University of Crete, Department of Production Engineering and Management, Chania 73100 Greece

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ABSTRACT

This article presents an artificial intelligence-based solution to the problem of product line optimization. More specifically, we apply a new hybrid particle swarm optimization (PSO) approach to design an optimal industrial product line. PSO is a biologically-inspired optimization framework derived from natural intelligence that exploits simple analogues of collective behavior found in nature, such as bird flocking and fish schooling. All existing product line optimization algorithms in the literature have been so far applied to consumer markets and product attributes that range across some discrete values. Our hybrid PSO algorithm searches for an optimal product line in a large design space which consists of both discrete and continuous design variables. The incorporation of a mutation operator to the standard PSO algorithm significantly improves its performance and enables our mechanism to outperform the state of the art Genetic Algorithm in a simulated study with artificial datasets pertaining to industrial cranes. The proposed approach deals with the problem of handling variables that can take any value from a continuous range and utilizes design variables associated with both product attributes and value-added services. The application of the proposed artificial intelligence framework yields important implications for strategic customer relationship and production management in business-to-business markets.

1. Introduction

Product line design is a critical task that may determine a firm's survival. Product lines need to constantly evolve in response to market and technology changes. The process of developing a product line is costly, whilst the failure rates of new products are alarmingly high. As a result, the determination of optimal product lines has attracted considerable attention in the marketing literature. However, all optimization algorithms so far have been applied to products whose attributes are treated as discrete.

Contrary to existing product line optimization studies, the present application searches for optimal solutions in a very large, mixed design space, which consists of both discrete variables and variables that can take any value from a continuous range. Our approach makes the optimization problem much more realistic, given that, in practice, the design space of most products can be very large, virtually infinite and includes both discrete and continuous design variables (Luo, 2011; Michalek, Feinberg, Ebbes, Adigüzel, & Papalambros, 2011).

In real life, many product attributes are described in terms of continuous, real numbers. This is especially common in business-to-business markets, in which industrial products are often specified in terms of continuous variables such as weight, length, speed, capacity, power, energy, time etc. Existing approaches virtually convert the continuous attributes to discrete ones by defining just a set of values (i.e., attribute levels), usually the upper and the lower limit of the attribute's continuous range, along with a few representative points within the range. Obviously, this constitutes a very restrictive assumption, which on the one hand may reduces the problem's complexity, but on the other hand may also lead to less than optimal solutions and thus, less than maximum profits and sales for the firm. Let's imagine for example a hypothetical product design scenario in which the researcher considers two continuous attributes. If both attributes are treated as discrete and range across three levels each, the solution space of the single-product line problem will consist of nine candidate optimal solutions. On the other hand, if the attributes are treated as continuous, the algorithm will search for the optimal product

* Corresponding author. Tel.: +30 28210 37160; fax: +30 2821069410.
E-mail addresses: tsafarakis@dpem.tuc.gr (S. Tsafarakis), b.saridakis@leeds.ac.uk (C. Saridakis), gb@aueb.gr (G. Baltas), nikos@ergasya.tuc.gr (N. Matsatsinis).
[1] Tel.: +44 113 343 1710.
[2] Tel.: +30 210 8203 714.
[3] Tel.: +30 28210 37348.

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configuration across an "infinite" set of candidate solutions. The inclusion of continuous variables into the design space may increase the problem's complexity, but at the same time, the problem becomes much more realistic. Additionally, its applicability for practical engineering problems increases, whilst the researcher can manage complex relationships among attainable combinations of product attributes that could not be easily handled through attribute discretization.

In this paper we propose a new method for optimizing a line of products which consist of both discrete and continuous attributes. Specifically, we design a hybrid particle swarm optimization (PSO) algorithm with mutation and implement it to a business-to-business context. The implementation of our mechanism to an industrial setting yields important managerial implications for strategic customer relationship and production management. The study contributes to the literature by proposing an optimization method that works in relatively large-scale design problems consisting of both discrete and continuous design variables and provides an efficient solution to the focal manufacturer's design variable configuration problem. To the best of our knowledge this is the first study that optimizes an industrial product line that incorporates continuous attributes.

The remainder of the article is organized as follows. The next section discusses the theoretical background with particular emphasis on the product line design literature. The third section develops the proposed hybrid PSO algorithm, which is then implemented to a case study concerning industrial cranes. A concluding section summarizes the paper and provides useful implications for managers and researchers.

2. Relationship to existing research

2.1. Product line design research streams

The optimal product design problem was introduced by Zufryden (1977). Eight years later Green and Krieger (1985) formulated the optimal product line design problem, i.e., a product line that optimizes a specific objective, usually profit or market share. The extensive literature on product line design has been surveyed in Lancaster (1990), Eliashberg and Steinberg (1993), Krishnan and Ulrich (2001), Ramdas (2003), and Tsafarakis and Matsatsinis (2010).

The literature reflects two main research streams, namely, marketing and engineering. There are also some researchers who have integrated both research streams into the design of either a single product (e.g., Besharati, Luo, Azarm, & Kannan, 2004, 2006; Griffin & Hauser, 1993; Hauser & Clausing, 1988; Li & Azarm, 2000; Luo, Kannan, Besharati, & Azarm, 2005; Michalek, Feinberg, & Papalambros, 2005; Srinivasan, Lovejoy, & Beach, 1997; Tarasewich & McMullen, 2001; Tarasewich & Nair, 2001) or a line of products (e.g., D'Souza & Simpson, 2003; Heese & Swaminathan, 2006; Jiao & Zhang, 2005; Li & Azarm, 2002; Michalek, Ceryan, Papalambros, & Koren, 2006).

According to the engineering perspective, researchers focus on platform management and strive for balance between the commonality of the product platform and the individual product's engineering performance (e.g., Farrell & Simpson, 2003; Rai & Allada, 2006; Simpson, Seeperad, & Mistree, 2001).

According to the marketing perspective, researchers usually employ conjoint or simulated data and search for an optimal or near-optimal product line, based on discrete levels of attributes (e.g., Balakrishnan, Gupta, & Jacob, 2006; Chen & Hausman, 2000; Dobson & Kalish, 1988, 1993; McBride & Zufryden, 1988; Moore, Louviere, & Verma, 1999; Selove & Hauser, 2010). Every product in the line is composed of a number of attributes, and conjoint analysis is used for measuring consumer preferences for those attributes. So far, all existing studies have considered product attributes that could take just a limited number of discrete values (i.e., attribute levels). Conjoint analysis is usually applied in order to provide an index for each attribute level (i.e., partworth), which represents a relative measure of utility. The overall product utility is then given by the sum of the partworth values that have been estimated for each of the attribute levels that the product possesses. Product utilities are converted to choice probabilities for each product through the use of a choice rule. In the case of market share maximization, the overall market share of a product line is derived from the aggregation of the choice probabilities across the entire sample. Finally, the application of an optimization algorithm provides the configuration of the product line, which maximizes the firm's market share.

From the foregoing analysis, it becomes evident that the product line design optimization problem can easily become too large. Actually it belongs to the NP-hard class of optimization problems (Kohli & Krishnamusti, 1989) and thus different heuristic procedures have been proposed as a means to provide near optimal solutions in tractable time, including Dynamic Programming (Kohli & Sukumar, 1990), Beam Search (Nair, Thakur, & Wen, 1995), and Lagrangian Relaxation with Branch and Bound (Belloni, Freund, Selove, & Simester, 2008; Camm, Cochran, Curry, & Kannan, 2006). Recently, nature-inspired approaches have been also introduced to the problem, including Genetic Algorithms (GAs) (Alexouda & Paparrizos, 2001; Balakrishnan, Gupta, & Jacob, 2004; Steiner & Hruschka, 2003), Ant Colony Optimization (Albritton & McMullen, 2007), and PSO (Tsafarakis, Marinakis, & Matsatsinis, 2011).

2.2. Recent studies in the literature

Although the problem of optimal product line design has been heavily studied in literature over the past 30 years, it still remains an interesting and exciting topic of research with several publications in recent years. For example, Luo, Kannan, and Ratchford (2008) extended the optimal product line design problem to incorporate consumer preferences for both objective and subjective product characteristics, whilst Belloni et al. (2008) provided a detailed review of heuristic mechanisms that have been recently introduced to the problem, such as Coordinate Ascent, GAs and Simulated Annealing.

Kumar, Chen, and Simpson (2009) introduced a novel methodology which examines the impact of increasing product variety across different market segments, whilst taking into account the cost-savings associated with commonality decisions. Kannan, Pope, and Jain (2009) focused on pricing issues by analysing purchase patterns in a product line under substitute or complement situations. Farrell and Simpson (2010) introduced a method to analyze the manufacturing costs of highly customized, low volume product lines.

Among the most pioneering studies of the last two years are the ones of Michalek et al. (2011) who presented a unified product line design methodology that coordinates positioning and design models and the study of Luo (2011) that presented a product line optimization method which enables managers to simultaneously consider factors from both marketing and engineering domains. Both studies have underlined the limitation of all existing applications regarding their focus on discretized design spaces.

Finally, Kuzmanovic and Matric (2012) proposed a new conjoint-based approach to competitive new product line design, employing the Nash equilibrium concept, whilst Lacourbe (2012) investigated the impact of external options, represented by reservation utility, on product line design and introduction sequence.

2.3. Contribution of the current study

As noted earlier, previous studies have limited the composition of a product line to a set of products that could range among some discrete values, usually predefined by the researcher. In technical terms, due to the complexity of the product line design problem, previous applications have traditionally searched for optimal solutions in design spaces which consist of discrete design variables. However, in practice, the design spaces of most products are very large, virtually infinite (Luo, 2011; Michalek et al., 2011).