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The component commonality problem in a real multidimensional space: An algorithmic approach

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ABSTRACT

Component commonality is an efficient mechanism to mitigate the negative impact of a highly diversified product line. In this paper, we address the optimal commonality problem in a real multidimensional space, developing a novel algorithmic approach aimed at transforming a continuous multidimensional decision problem into a discrete decision problem. Moreover, we show that our formulation is equivalent to the k-median facility location problem. It is well known that when several dimensions are included and components' features are defined in the real line, the number of potential locations grows exponentially, hindering the application of standard integer programming techniques for solving the problem. However, as formulated, the multidimensional component commonality problem is a supermodular minimization problem, a family of problems for which greedy-type heuristics show very good performance. Based on this observation, we provide a collection of *descent-greedy* algorithms which benefits from certain structural properties of the problem and can handle substantially large instances. Additionally, a MathHeuristic is developed to improve the performance of the algorithms. Finally, results of a number of computational experiments, which testify for the good performance of our heuristics, are presented.

1. Introduction

In a highly competitive globalized world, firms increasingly face the need of providing an enlarged product variety in order to satisfy a hugely diversified market. This increased variety of products demands a large number of different components and configurations that usually exceed by far the capabilities of the assembly line. Moreover, as Bernstein, Kök, and Xie (2011) point out, a larger number of variants of the same product increases the manufacturing complexity and leads to a more fragmented product line. This, in turn, reduces the capability of the firm for taking advantage of economies of scale.

Component commonality is one of the most efficient mechanisms to mitigate the negative impact of a large number of product variants. Thonemann and Brandeau (2000) provide the example of one major automobile manufacturer that offers a particular model in more than one billion combinations of colors, interior designs, drive train configurations, and option choices. Clearly, this level of diversification can only be attained by the use of common components in some models. According to these authors, most automotive companies have recognized the benefits of component commonality and have developed car models that share components ranging from standardised commodity parts to complicated sub-assemblies. More recently, Greimel (2013) describes the redesign of the Nissan Rogue crossover, the first product of a new modular development strategy that aims to cast down costs. He emphasizes that Nissan's engineers redesigned 84 component systems to make them common with systems used by Renault, Nissan's alliance partner. The goal was to standardise parts for 1.5 million units over 14 models.

Many benefits have been argued on the use of component commonality in the production line. Among them, Subramanian, Ferguson, and Toktay (2013) mention the reduction in unit production costs due to the existence of economies of scale, savings in inventory costs and mitigation of shortage costs due to risk pooling. On the other hand, the use of common components imposes additional costs, as there is a loss derived from using a higher performance component in a bottom-line product. Moreover, the manufacturing cost of a product may be increased if it has to be adapted for using a component with higher specifications than necessary (Subramanian et al., 2013). Given this trade-off, the firm faces the need of determining the

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number and specification of the common components to be shared by its products.

Over the last few years, the problem of component commonality has received increasing attention from both practitioners and academics. On the industrial side, it is easy to find examples of the recent debate on the issue of standardisation and component commonality. For example, in a recent webinar organized by SCM World, Fuganti[1] discussed product complexity and component commonality. The following text is extracted from the webinar and appeared in print on the May 7, 2014, edition of SCM World (Fuganti, 2014):

> *Increased product complexity, greater customer personalisation and the need to get new models to market faster are among the top challenges facing auto makers today. One of the main ways the auto industry is addressing these challenges, while trying to preserve the economies of scale on which it has long depended, is through modularity in product design. This leads to standard platforms, or architectures, and the reuse of common systems and components across different models.*

Through the same media, Lemoine[2] discusses how the methodology of value analysis and value engineering can "be used to ask key questions of the manufacturing process to enable cost reduction with minimal resources" (Lemoine, 2013). Among these questions, he mentions the possibility of parts standardisation and the introduction of new product specifications to reduce costs.

On the academic side, there is a vast amount of literature addressing different aspects of the component commonality problem. For example, Briant and Naddef (2004) discussed the case of European auto assembly plants requiring 7000 different wiring designs. In their example, the number designs indeed produced is two orders of magnitude smaller than that value. Bernstein, DeCroix, and Wang (2007) presented the case of Dell Computers where a wide variety of ending products is obtained from a more limited number of components. Finally, Subramanian et al. (2013) mention the case of Caterpillar, where important benefits have been obtained since 2008 through the use of component commonality in their products.

This paper provides a methodology for determining the attributes of a limited number of components, aimed at satisfying the requirements of a larger set of products at a minimal cost. It considers a multi-dimensional attribute space for a single component, where each attribute can take either continuous or discrete values. Our work extends the available literature on the component commonality problem as, to our knowledge, no one has yet worked on continuous multi-dimensional problems. Indeed, most of the available research is limited to the analysis of commonality problems with binary or discrete attributes. Moreover, although the problem has been extensively studied in literature, most of the available applications are aimed at deciding, out of a collection of pre-defined modules, which one should be brought to the market. Based on the observation that, after a suitable modification of the specification space, the multidimensional component commonality problem is mathematically equivalent to the k-median problem, the algorithmic approach developed here provides researchers and practitioners with a simple procedure that can easily be used in real life applications. Additionally, the proposed technique grants the decision makers more freedom on the designing phase, eliminating the need for pre-defined modules.

Finally, the tools developed in this paper can be used to solve commonality problems in areas as diverse as agro-industrial and heavy industrial machinery production, aerospace and automotive industries, photography and image processing, and computers and networking equipment manufacturing, among others. To illustrate this applicability and to further stress the relevance of the techniques developed in this paper, in the following lines we present a hypothetical example based on a real life problem faced by car manufacturers.

Let us start by illustrating the use of a common platform in a variety of cars with a wide range of weights. Toyota's Camry has a Gross Vehicle Weight Rating (GVWR) of 2100 kilogram on its heavier version. Camry's platform is also used, among others, by Sienna – a minivan by Toyota, which has a GVWR of 2715 kilogram on its heavier version; and by Highlander, which has maximum GVWR of 2720 kilogram and of 2840 kilogram on its non-hybrid and hybrid versions, respectively. An additional element that increases the total weight of a vehicle is the towing. While the smaller Sienna has a towing capacity between 454 kilogram and 1548 kilogram, the hybrid Highlander can tow up to 1587 kilogram, and the non-hybrid up to 2268 kilogram -it was not possible to find Camry's official towing capacity. These numbers illustrate that the total weight of cars using the same platform may vary within a range of about 800 kilogram without towing, and up to 2500 kilogram when towing is considered (it is important to notice that even though GVWR and towing capacity values come in a range, in practice they are summarized by the heaviest of the vehicles, which broadens the weight ranges given before)[3].

In the USA market alone, 2014 sales were approximately 428,000 units for Camry, 146,000 for the two Highlanders, and 124,000 for the Sienna; making a total of near 700,000 cars sold in 2014[4].

With these figures in mind, consider the case of a large car manufacturer who has to make choices about certain structural element whose capacity for withstanding forces is crucial. Take, for example, the brake pad, a piece whose characteristics are related to the final weight of the car, including towing. This piece is used across different platforms, with several different models using the same platform, which altogether may sell several million cars worldwide every year. Brake pads, according to Toyota, are made from five main groups of materials: binding materials (binders); abrasive materials (for example, mineral fillers used to boost friction); performance related materials (included in precise amounts to enhance certain braking characteristics, e.g. temperature specific lubricants); filling materials (e.g. rubber or rubber scrap that can increase wear resistance); and structural materials (which help the pad to maintain proper shape during use). According to Toyota's website, "these five types of materials encompass more than 2000 substances"[5].

The above discussion highlights a potential application of the formulation and methodology developed in this paper, where all the elements of a typical component commonality problem are present: a collection of different car models and platforms uses a common part, whose attributes vary depending on the specific requirements of each model (related to their weight and towing capacity). Those requirements are quantified in continuous metrics. On the other hand, the parts materials are also quantified in continuous metrics with, at least, five different dimensions. The car maker should decide on the number of different brake pads' versions to produce, their physical characteristics, and the allocation of the various versions to the different platforms and car models that will use them.

The rest of the paper is structured as follows. In Section 2 we review the existing literature in component commonality. Section 3 introduces our model and presents some structural properties. In Section 4 we develop an algorithmic approach for addressing large instances of the problem. A numerical assessment of approach is

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[3] For these and further details on Toyota's cars GVWRs and towing capacities visit, for example, http://www.car.com, http://www.edmunds.com or http://www.toyota.ca.

[4] For complete details on 2014 sales, please see http://toyotanews.pressroom.toyota.com/sales-financial/releases/.

[5] For further information, please visit https://parts.olathetoyota.com/what-are-brake-pads-made-of.html