Optimisation of the Variant Combination of Control Units Considering the Order History

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Summary. In modern cars, an increasing number of functions are integrated in single control units. Some of the functions can be ordered as optional equipment by the customer. To reduce costs, variants of the control units are created differing in hardware and software. Variants are created by not populating sections of a circuit board. Each additional variant of a control unit causes expenses for logistics and development. Today the process for the determination of the variants is not automated. Non-technical dependencies like equipment packages or common ordered equipment combinations can only partially be taken into account. In this article we formulate this problem and show how existing information on the manufacturer's side can serve as a base for an optimisation of the variants. We also show how the problem can be transformed into a warehouse location problem, so that it can be solved in short time. Finally, the results of an application example are presented.

1 Introduction

The functionality of modern cars is steadily increasing. Most of these functions are designed to increase comfort and safety. In order to cope with the trend towards more functions and the cost pressure, an increasing number of functions are integrated in single control units.

Functions that can be ordered as optional equipment by the customer are often performed by electronic control units, which have to be put in every car. In an effort to reduce costs, variants of these control units are created, which differ in hardware and software. The variants are designed, for example, by not populating sections of a circuit board. Each additional variant of a control unit demands high efforts in logistics and development. For this reason, it is mostly not possible to install tailor-made control unit variants for all possible orders.

Today the determination of the variants is based on equipment order rates and technical inter-dependencies. This process is complex and not automated. Non-technical dependencies like equipment packages or common ordered equipment combinations can only partially be taken into account.

This article describes how the cost-optimal variants can be determined. In Sect. 2, the problem will be described more in detail. Afterwards (Sect. 3), it will be explained how data, required for a variant combination optimisation, can be gathered. The mathematical problem description will be presented in Sect. 4, before the transformation of the variant combination problem into a warehouse location problem is shown (Sect. 5). Finally the cost reduction potential of the variant optimisation will be presented (Sect. 6).

2 Problem Description

This section gives an overview of the variant combination problem (VCP). After the definition of special terms, it will be described how the number of variants can be reduced by deactivating not ordered functions in control units. Furthermore, it will be explained how the average costs for a manufacturer can be calculated.

2.1 Terms and Definitions

The electronic system in a vehicle has to implement several *functions* or *features* f. During the development of a car, for each *electronic control unit (ECU)*, the features F_{ECU}, which have to be supported, are defined. The customer in turn decides which combination of features and properties his car should cover – the configuration of his vehicle. This influences the features that every ECU has to implement. The according set of features $F_l \subseteq F_{ECU}$ for each single car and per ECU is called *feature combination*. In this article, only optional features, which do not belong to the standard equipment, are considered.

An ECU can also be seen as composed of technical components. Each *component* c_k of an ECU supports one or more features and is therefore required by these features. On the other hand, a feature sometimes requires more than one component. As for the features, in the following, only optional components are considered, since the optimisation result is not influenced by components that all vehicles contain. For convenience, the word *optional* is left out, and it is just spoken of components and features.

Based on the relations between features and components of an ECU, it is possible to determine all components that are required to support the ordered feature combination F_l of an ECU. This combination of components is called *(minimal) component combination* $C_{F_l}^{\min}$, because no component can be removed without losing the ability to support all ordered features.

Variants v of ECUs can also be considered as combinations of components. They are built in cars to satisfy the demand for features. The variant being installed in an ordered car has to be a superset of the component combination. This means that variants sometimes support more components than required. The components in that ECU can be deactivated without being visible to the customer. A set of variants used for all orders of a vehicle type is called variant combination V_q. A variant combination is valid if for each component combination, at least one variant can be found being a superset.

2.2 Quality of a Combination of Variants

The sum of the average hardware costs and the handling costs for the variants reflect the quality of a variant combination. Both cost types depend on the number of variants. The more variants are managed, the lower the material costs $\tilde{c}$, but the higher the overall handling costs $\tilde{f}^c = \tilde{f} \cdot m$ (see Fig. 1).[3] The optimal number of variants m^* can be found where the sum $\tilde{F}$ of both costs has its minimum.

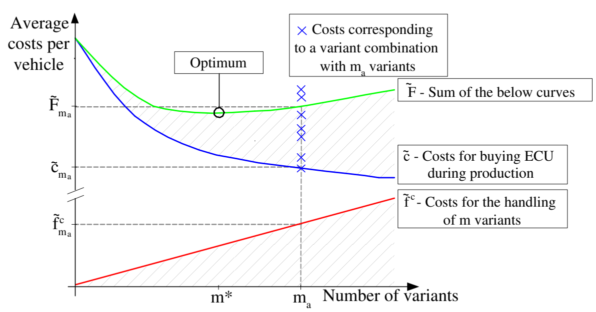

Fig. 1. Average costs dependent on the number of variants

The determination of the hardware costs depends on the chosen variant combination V_q. For each valid variant combination V_q, the corresponding cost $\tilde{c}^{V_q} = \sum_{\forall v_i \in V_q} p_i \cdot r_i$ can be calculated using the variant price p_i and the according installation rate r_i of all variants. The installation rates r_i depend on the customer orders. For each order the cheapest variant of V_q that supports all required functions is built in.

Usually, there is more than one valid variant combination that contains a defined number of variants. In Fig. 1 "x" indicates the costs $\tilde{c}^{V_q}$ for dif-

[3] For simplification, it is assumed that each additional variant causes the same order-independent costs $\tilde{f} = \tilde{f}^c/m$, where m represents the number of variants in the variant combination.

ferent variant combinations with m_a elements. The minimum of the costs corresponding to these variant combinations with m_a elements belongs to the optimal variant combination V^{m_a} with exactly m_a elements. Connecting the cost points of all optimal variant combinations V^m $(m = 1, 2, \dots)$, the curve $\tilde{c}$ in Fig. 1 can be constructed.

3 Data Determination

This section explains how all information for the determination of the optimal variant combination can be gathered:

- *The predicted "order numbers" n_j of all component combinations $C_j^{\min}$*
  For the calculation of the order numbers n_j, the feature combinations F_l of the future car orders must be known. To create an order forecast, past customer orders can be used. Some additional information is necessary in order to consider new features and customer behaviour. Using the relations between features and components (see Sect. 2.1), each feature combination F_l can be transformed into a corresponding component combination $C_j^{\min}$. For all $C_j^{\min}$ the according order number n_j can be determined as well by aggregation.
- *The prices p_i of the variants v_i*
  We assume that the price p_i of a variant v_i is composed of a base price p^{basis} for the control unit with the standard components and the respective prices p^{c_k} of the components c_k that are implemented additionally. It is sufficient, to add up only the prices p^{c_k} of the implemented components $c_k \in v_i$ because the constant base price does not influence the optimisation ($p_i = \sum_{c_k \in v_i} p^{c_k}$).
- *The cost relations $\tilde{c}_{ij}$ between each component combination $C_j^{\min}$ and each possible variant v_i*
  For a specific component combination $C_j^{\min}$, only those variants containing at least all components of $C_j^{\min}$ can be installed. For all these variants v_i, the product of their price p_i and the order number n_j of the component combination $C_j^{\min}$ equals the costs $\tilde{c}_{ij}$ that arise if in all cars that require the component combination $C_j^{\min}$, variant v_i is installed. For all other couples ij, the corresponding cost $\tilde{c}_{ij}$ can be set to a high value M. The high value ensures that the optimisation algorithm does not assign a "not allowed" variant v_i to the component combination $C_j^{\min}$. Thus, the cost $\tilde{c}_{ij}$ can be explained as follows: $\tilde{c}_{ij} = \begin{cases} n_j \cdot p_i & \text{if } C_j^{\min} \subseteq v_i, \\ M & \text{else.} \end{cases}$
- *The costs $\tilde{f}$ for handling an additional variant*
  The costs $\tilde{f}$ for the development, administration, and handling of an additional variant can be estimated using past values. This can be difficult, since various divisions of a car manufacturer get in contact with ECUs, and so all these divisions have to evaluate the costs caused by the variants.

4 Mathematical Problem Description

Besides the identifiers for the data values (see above), the variables y_i and x_{ij} are used to describe the problem. The meaning of these variables in a valid solution of the VCP is:

- $y_i = 1$, if variant i belongs to the variant combination, $y_i = 0$ otherwise,
- x_{ij}, percentage of the orders n_j of C_j^{Min} that are satisfied by the installation of v_i. Should be 1 or 0 after the optimisation.

With these variables and identifiers, the VCP can be formulated as follows:

$$\text{Min. F}(\mathbf{x,y}) = \sum_i \sum_j \tilde{c}_{ij} \cdot x_{ij} + \sum_i \tilde{f} \cdot y_i \tag{1}$$

with the constraints

$$x_{ij} \leq y_i \qquad \forall i \text{ and } \forall j \tag{2}$$

$$\sum_i x_{ij} = 1 \qquad \forall j \tag{3}$$

$$y_i \in \{0, 1\} \qquad \forall i \tag{4}$$

$$x_{ij} \geq 0 \qquad \forall i \text{ and } \forall j \tag{5}$$

The constraints (2) ensure that orders of component combinations are only satisfied by variants that are elements of the variant combination. For each component combination the corresponding constraint (3) guarantees, that all orders of this component combination are fulfilled. The ranges of the variables are restricted by the constraints (4) and (5).

5 VCP as a Warehouse Location Problem

Similar to our VCP is the (uncapacitated, simple) warehouse location problem (WLP)[4]. In a WLP, customers with demands n_j for one homogeneous product are given. They are supplied from some warehouses, which are not established yet. There exist some places where warehouses could be established. Opening a warehouse at place i causes costs equal to $\tilde{f}$. The transportation of one unit of the product from the possible place i of a warehouse to customer j costs p_{ij} and the transportation of the whole demand n_j costs $\tilde{c}_{ij} = p_{ij} \cdot n_j$. The question is at what places warehouses should be opened and from which opened warehouse the customers should be delivered, so that the overall costs are minimal. The VCP can be seen as a WLP. Therefore, the following transformations have to be done:

[4] This problem is also called the uncapacitated facility location problem or simple plant location problem (SPLP).

Table 1. Transformation of a VCP into a WLP

	VCP	**WLP**
j	component combination j	customer j
i	possible variant i	possible warehouse location i
y_i	equals one, if variant i belongs to the variant combination, else zero	equals one, if at location i a warehouse has to established, else zero
x_{ij}	$x_{ij} \cdot 100$ percent of the orders of component combination j is satisfied by the installation of variant i	$x_{ij} \cdot 100$ percent of the demand of the customer j is satisfied by the warehouse at the location i
$\tilde{c}_{ij}$	costs if variant i is built in all cars that require comp. combination j	costs if warehouse of location i covers the whole demand of customer j
$\tilde{f}$	costs for developing and handling the additional variant i	costs for building and administration of the additional warehouse i

Thus, both problems can be described mathematically in the same way ((1)-(5) see also [1, p. 52] and all solution methods that are available for the WLP can be used to solve the VCP. Besides heuristic methods, especially Branch & Bound procedures are available to solve the WLP [1, p. 78]. An efficient and exact one that was developed by Erlenkotter is presented in ([2, p. 215ff.]).

6 Conclusions

The determination of the cost-optimal variants of a control unit can be simplified and improved by a computer-aided optimisation. One of the first applications of this procedure was the variant optimisation of a control unit with 10 (optional) components. In comparison to a previously realised manual variant determination, using computer-aided optimisation can save about one euro per car if the future orders exactly match the forecast. We have also tested the results using varying forecasts. It can be shown that the results are relatively stable and represent a big improvement over the manual determination of the variants.

References

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