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Application of product family design for engineered systems in changing market space

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APPLICATION OF PRODUCT FAMILY DESIGN FOR ENGINEERED SYSTEMS IN CHANGING MARKET SPACE

by

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ABSTRACT

The focus of this paper is on the design of an engineered system for a changing market space. Due to the dynamic nature of the customer requirements, the specification of product offerings in a particular market may change. Manufacturers need to strategically design their product portfolio in such a way that their profitability is maximized, while deploying the right number of platforms necessary for deriving product variants. Depending on the system architecture, subsystems can be classified into one of the two types: scalar subsystems and modular subsystems. Each subsystem is defined by various parameters, performance criteria, and physical compatibility constraints. The market demand is modeled as a function of selling price and performance criteria. The objective function is formulated as maximization of total profitability for the current and future markets while meeting the required performance criteria. The profitability of an individual unit is the difference between the selling price and cost of that particular unit. The selling price has been expressed as a linear function of system characteristic and performance parameters. The cost of an individual system is the sum of the cost of all the subsystems involved. The cost of an individual subsystem is a function of parameters of that particular subsystem. Further, different types of technology are considered available at different time periods that impacts the switchover cost. The total profitability is further reduced by the platform development cost of the variants. The complete engineered system level problem is formulated as a non-linear programming optimization problem and solved using the non-linear generalized reduced gradient algorithm. The application of the proposed methodology is demonstrated using a case example of an automotive truck family.

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APPLICATION OF PRODUCT FAMILY DESIGN FOR ENGINEERED SYSTEMS IN CHANGING MARKET SPACE

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The focus of this paper is on the design of an engineered system for a changing market space. Due to the dynamic nature of the customer requirements, the specification of product offerings in a particular market may change. Manufacturers need to strategically design their product portfolio in such a way that their profitability is maximized, while deploying the right number of platforms necessary for deriving product variants. Depending on the system architecture, subsystems can be classified into one of the two types: scalar subsystems and modular subsystems. Each subsystem is defined by various parameters, performance criteria, and physical compatibility constraints. The market demand is modeled as a function of selling price and performance criteria. The objective function is formulated as maximization of total profitability for the current and future markets while meeting the required performance criteria. The profitability of an individual unit is the difference between the selling price and cost of that particular unit. The selling price has been expressed as a linear function of system characteristic and performance parameters. The cost of an individual system is the sum of the cost of all the subsystems involved. The cost of an individual subsystem is a function of parameters of that particular subsystem. Further, different types of technology are considered available at different time periods that impacts the switchover cost. The total profitability is further reduced by the platform development cost of the variants. The complete engineered system level problem is formulated as a non-linear programming optimization problem and solved using the non-linear generalized reduced gradient algorithm. The application of the proposed methodology is demonstrated using a case example of an automotive truck family.

KEYWORDS: Engineered systems, Product platform, system architecture, and automotive truck.

Notations and variables

Notations

i = Index for each variant.

j = Index for each of the individual subsystems.

Variables

SP_{GVW} = Selling price coefficient per unit of ton ($ 2000/ton)

SP_{HP} = Selling price coefficient per unit of horsepower ($ 220/hp)

$X_{(EngTor)\ i}$ = Engine Torque (Nm) for variant i.

$X_{(RPM)\ i}$ = Maximum Engine RPM for segment i.

$X_{(RPM\ o)\ i}$ = Operational Engine RPM for variant i.

$X_{(HP)\ i}$ = Engine Horsepower (HP) for variant i.

$X_{(GbTor)\ i}$ = Gear Box Torque capacity (Nm) for variant i.

$R_{(GB)\ i}$ = Gear Box first ratio for variant i.

$R_{(GB2)\ i}$ = Gear Box second ratio for variant i.

$X_{(ClTor)\ i}$ = Clutch torque capacity (Nm) for variant i.

$X_{(ClFa)\ i}$ = Clutch friction area (Cm^2) for variant i.

σ_{cl} = Yield stress of material being used for clutch lining ($2.8N/cm^2$) for variant

$X_{(PsTor)\ i}$ = Propeller shaft torque capacity (Nm) for variant i.

$X_{(PsL)\ i}$ = Propeller shaft length including UJ & flange (m) for variant i.

ή = Transmission efficiency (85%).

$X_{(FmL)\ i}$ = Frame length (mm) for variant i.

$X_{(FmD)\ i}$ = Frame depth (mm) for variant i.

$X_{(FmW)\ i}$ = Frame web width (mm) for variant i.

$X_{(FmT)\ i}$ = Frame thickness (mm) for variant i.

σ_y = Yield strength of long member material (Nmm^{-2}) for variant i

$X_{(FaSlc)\ i}$ = Load capacity of front axle with suspension (Tonnes) for variant i.

$X_{(FaW)\ i}$ = Weight of the front axle (Ton) for variant i.

$X_{(RaSlc)\ i}$ = Load capacity of rear axle with suspension (Ton) for variant i.

$X_{(Cwpr)\ i}$ = Crown wheel & pinion ratio for variant i.

$X_{(CnL)\ i}$ = Max cabin length (m) for variant i.

$X_{(CnW)\ i}$ = Max cabin width (m) for variant i.

$X_{(CnH)\ i}$ = Max cabin height (m) for variant i.

$X_{(FtC)\ i}$ = Fuel tank capacity (liters) or variant i.

$X_{(BrTor)\ i}$ = Braking torque (Nm) for variant i.

$X_{(WtSw)\ i}$ = Section width of tire (mm) for variant i.

$X_{(WtRd)\ i}$ = Rim diameter (mm) for variant i.

$X_{(WtRw)\ i}$ = Rim width (mm) for variant i.

$X_{(WtTid)\ i}$ = Total inflated diameter (mm) for variant i.

$X_{(Dyn)\ i}$ = Dynamic tire radius (mm) for variant i.

$X_{(StgSr)\ i}$ = Steering ratio for variant i.

$X_{(LbVc)\ i}$ = Load body volumetric capacity (m^3) for variant i.

$L_{(Eng)\ i}$ = Length of engine (mm) for variant i.

$L_{(Gb)\ i}$ = Length of gear box (mm) for variant i.

$L_{(Cl)\ i}$ = Length of clutch (mm) for variant i.

$L_{(Egc)\ i}$ = Combined length of engine, clutch and gear box for variant i.

$L_{(Oh)\ i}$ = Length of overhang (length after rear axle line) for variant i.

GVW_i = Gross vehicle weight of vehicle for variant i.

N = Total Number of variants (6).

I = Maximum inclination considered for brake torque calculation (45deg).

m = Total number of subsystems (13).

K = Number of rear tires.

l = Number of front tires.

G_i = Gradeability for variant i.

v_i = Velocity for the variant i.

C_d = Coefficient of air drag.

ρ = Air density (1.39 kg/m^3).

Se = Set of different subsystem platforms

Binary variables

$Y_{(Subsys)\ i}$ = 1, If i^{th} subsystem platform is chosen for development

0 Otherwise

Y_{Eng} = 1, If engine is compatible with the rest of the system.

0 Otherwise.

Y_{Gb} = 1, If gear box is compatible with the rest of the system.

0 Otherwise.

Y_{Cl} = 1, If clutch is compatible with the rest of the system.

0 Otherwise.

Y_{Ps} = 1, If propeller shaft is compatible with the rest of the system.

0 Otherwise.

Y_{Fm} = 1, If frame is compatible with the rest of the system.

0 Otherwise.

Y_{FaS} = 1, If front axle is compatible with the rest of the system.

0 Otherwise.

Y_{Ras} = 1, is compatible with the rest of the system

0 Otherwise.

Y_{Cn} = 1, If cabin is compatible with the rest of the system

0 Otherwise.

Y_{Ft} = 1, If fuel tank is compatible with the rest of the system

0 Otherwise.

Y_{Br} = 1, If brake is compatible with the rest of the system

0 Otherwise.

Y_{Wt} = 1, If wheels & tyres is compatible with the rest of the system

0 Otherwise.

Y_{Stg} = 1, If steering is compatible with the rest of the system

0 Otherwise.

Y_{Lb} = 1, If load body is compatible with the rest of the system

0 Otherwise.

1. Introduction

Many companies are adopting the strategy of platform based product development (Krishnan *et al.* 2001) which is the part of a broader strategy called mass customization (Pine, 1993, Willoughby 2006). Large companies such as Dell, Boeing, and UPS have adopted mass customization and have gained strategic advantage. This strategy is realized successfully through platform and product family design. Product family realization through platform design enables companies to share components, interfaces and process (design/ production, etc.) across the product family, thereby attaining cost and time efficiencies, technological leverage and market power. Thus a wide variety of product variants with flexible processes can be introduced. For instance, several product manufacturers such as Volkswagen, Boeing, Dell and Hewlett-Packard are aggressively implementing platform strategies and producing wide variety of product with few platforms (De Weck *et al.* 2003). A product platform is commonly defined as "A set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched" (Meyer *et al.* 1997). A product platform can be considered as collection of the common elements, especially the underlying core technology that is implemented across a range of products (McGrath *et al.* 1995). From a broader perspective, the platform-based product development may contribute to benefits including reduced product lead-times, reduced system complexities, reduced development and manufacturing cost, by providing an array of products for different market niches (Simpson *et al.* 2004). From the manufacturing perspective, the platform-based product development process may lead to reduced non-value added activities and enhanced flexibility and utilization of production facilities. Product platforming employ the approach of sharing systems, subsystems and components across different product ranges for satisfying various customer needs. One of the key concerns of sharing systems across product variants is the loss of distinctiveness. In order to derive different product variants from a set of product platforms, there should be trade-offs between commonality and distinctiveness. The trade-offs are based on several criteria such as customer needs, market demand, price, and product performance criteria. These criteria usually govern the extent of tradeoffs between commonality and distinctiveness (Simpson *et al.* 2001). Considerable research in the area of design and optimization of product families has yielded numerous methodologies and procedure for platform formation. Simpson *et al.* (2001) introduced the Product Platform Concept Exploration method for platforming the scalable products based on market segmentation originally proposed by Meyer *et al.* (1997). Dai *et al.* (2004) designed product platform using sensitivity and cluster analysis with an example of universal electric motor problem. Akundi *et al.* (2005) formulated a multi-objective design optimization model for the universal electric motor problem. In this research, apart from the two commonly used objective functions that are maximization of motor efficiency and minimization of motor mass, an additional objective function involving minimization of the variance coefficient was introduced. The variance coefficient measures the magnitude of variance of number of common parts. Kumar *et al.* (2004) employed the ant colony optimization method for optimizing scalable product platforms by considering the performance loss of individual product variants. Rai and Allada (2002) used an agent based pareto-optimization method to demonstrate modular product family design concepts for electric knife and power screw driver families. This methodology also developed novel application of the quality loss function to determine the optimal platform level for a related set of product families and their variants.

Otto and Sudjianto (2001) discussed architecture design for multiple platforms supporting multiple brands considering the uniqueness of brand specific elements. De Weck *et al.* (2003) introduced a quantitative methodology to determine the optimum number of platforms to maximize profit for introducing product variety. The profit is a function of the market demand volume and cost of the product. The methodology considers trade-offs between the target performance requirements of the market segment and the manufacturing cost associated with an identified product family. Product family with multiple product system architecture and configuration was optimized by Fujita *et al.* (2002). The important contribution of this paper was commonality considerations for modules as well as attributes and optimization for multiple products based on same, similar and independent design. The problem was demonstrated using a case of commercial aircrafts. Araque *et al.* (2004) introduced a systems framework for platform architecture analysis. This framework considered three levels of analysis namely: individual products in a product family, platforms being leveraged across family, and potential of evaluation for product/platform family. Kulkarni *et al.* (2005) devised a method to design product platforms for a changing market space. This methodology was demonstrated using the example of pressure vessel problem. The changing market space refers to the change of demand in market segments over a given time horizon.

One of the important considerations for manufacturers while designing the product platforms are changing customer requirements and evolving technologies.

Changing customer requirements may lead to the possible expansion/shrinkage of the market space.

Figure 1 shows the current and future market spaces for an automotive truck market by considering two major parameters, namely: the load carrying capacity and the engine power.

Let the market space be MS1 at time T1 and MS2 at time T2. There can be two options for the manufacturer to capture this new market space MS2 and provide its product portfolio to entire market space (MS1 + MS2).

Option 1: Design a second product platform for market space MS2. As a result, there are now two adjacent product platforms in the market space MS1 and MS2.

Option 2: Extend the product platform in MS1 to accommodate the adjacent high demand market space MS2. As a result, there is a single large product platform in market space (MS1 + MS2).

Now consider the first option, which is a case of multiple product platforms. According to Seepersad *et al.* (2000), this kind of situation is beneficial only if there are gaps in the market space.

Consider the second option. The already existing product platform is designed considering the specifications of that particular market MS1. So extension of this product platform in the new market space MS2 may increase costs considerably. So in order to avoid this situation, one would have to redesign the entire product platform for the new market space (MS1+MS2). This may mean large restructuring cost for the manufacturer.

One of the questions that is addressed in this paper is how a manufacturer can strategically design product platforms under changing market space considerations. The product family roadmap provides information on the product variants belonging to different product families that are planned for release, and their time of introduction in a given planning horizon. (Wheelright and Sasser 1989, Meyer and Lehnerd 1997). Gillette has implemented such a product platform roadmap for its razor cartridge with the derivative products from Mach3 (Simpson *et al.* 2006).

In this paper, a framework has been presented for the changing market space and technology upgradation for an engineered system. Due to the changing market space with respect to the time, the demand will also vary, which in turn, will be one of the factors to determine efficient platform architectures. In this research, the engineered system is composed of various systems which are made of a number of subsystems. Each system and then subsystems are defined by various independent and interrelated parameters. The selection of a particular system and subsystems configuration will be influenced by the selection of other system configurations. For example, in this paper the automotive truck has been considered as an engineered system. Automotive truck is made up of a number of systems namely: power train system, load bearing system, body system, etc. Each of these systems consists of many subsystems. For example, the power train system is composed of subsystems like the engine, gear-box, clutch, and propeller shaft. Each of these subsystems is governed by their respective parameters. As an example, the engine is defined by parameters such as the horse power, torque, and rpm.

2. Problem framework

2.1 Identification of key performance parameters

In this problem, the following two parameters are specified as the key performance criteria:

Gross vehicle weight (GVW):- The gross vehicle weight of a truck is defined as the summation of its own weight and its maximum payload. The GVW is one of the key vehicle characteristic that is used to classify vehicles into different variant categories.

Gradeability: Gradeability of a vehicle is defined as the maximum inclination a vehicle can climb while maintaining adequate control. It is also concerned with the ability to accelerate and pull the vehicle from a standstill position. In general, the higher the gradeability the higher is the maximum attainable speed. For this problem, the contribution of air resistance is being taken into consideration. The gradeability is defined by the following equation:

$$\text{Gradeability (\%)} = \tan [\text{Sin}^{-1}\{(X_{(EngTor)\,i} * R_{(Gb)\,i} * X_{(CwPr)\,i} * \acute{\eta})/ (GVW_i * X_{(Dyn)\,i}) - (.5 * v^2 * C_d * \rho * X_{(CnH)\,i} * X_{(CnW)\,i})/(GVWi*X_{(Dyn)\,i})\}] \quad (1)$$

Where $X_{(EngTor)\,i}$ = Engine torque (Nm) for variant i.

$R_{(Gb)\,i}$ = Gear box first ratio for variant i.

$X_{(CwPr)\,i}$ = Crown wheel and pinion ratio for variant i.

n = Transmission efficiency

GVW_i = Gross vehicle weight for variants i.

$X_{(Dyn)\,i}$ = Dynamic tire radius for variant i.

v = Maximum velocity of truck

C_d = Coefficient of air drag

ρ = Air density

$X_{(CnH)\,i}$ = Cabin height for variant i.

$X_{(CnW)\,i}$ = Cabin width for variant i.

2.2 Establishment of current market space and demand

The broad parameters for defining the market space for automotive trucks are gross vehicle weight and engine horse power. The current market space contains three variants as shown in Table 1. Table 1 also denotes the market demand values for individual variants. The current market space is shown in Figure 2.

In this study, the demand of the individual product variant (truck) is modeled as a function of selling price and value. The best possible specification implies the best specification of the engine horsepower and gross vehicle weight (within the +10% maximum performance loss). The minimum acceptable specification implies the minimum acceptable specification of the engine horsepower and gross vehicle weight (within the -10% performance loss).

Assuming a monopolistic market, the demand for the individual product variant is estimated using Cook's (1997) demand model as given by equation 2.

$$D_i = K_i * (V_i - P_i) \tag{2}$$

Where

D_i = Demand of individual product variant i.

V_i = Value of product variant i.

P_i = Price of product variant i.

K_i = Absolute elasticity of demand.

The absolute elasticity of demand is the ratio of the change in demand corresponding to the change in price (De Weck 2000).

$$V_i=(SP_{HP}.HP_{maxi}+SP_{GVW}.GVW_{max\ i}) \tag{3}$$

$$P_i=(SP_{HP}.HP_{mini}+SP_{GVW}.GVW_{min\ i}) \tag{4}$$

Equations 3 and 4 represent the value and price respectively for the product variant i.

2.3 Exploration of the possible future market portfolio expansion and consolidation with current market space.

The possible future scenrios of market expansion are considered in this study. This involves forecasting of the market and assignment of probabilities to market expansion scenrios. The probabilities in this problem are conditional probabilities, i. e. the probability of existence of one variant given a particular market space. The result of this step is a number of possible portfolio expansions. Figure 3 depicts two possible market spaces in years 2 and 3, which are MS2 and MS3 respectively. The manufacturer wishes to introduce one variant in year 2 and two variants in year 3. The year two variant is denoted by V 2.1, while the year three variants are denoted by V3.1 and V3.2.

Figure 3 denotes the consolidated version of current and future market space. Table 2 provides the broad level specification and the conditional probabilities in future markets as well as the demand values for each of these variants. The demand is estimated using equation 2 described in section 2.2.

2.4 Development of technological roadmap

Refer to Figure 4 for the technology roadmap for the automotive truck example. These technologies will be evaluated essentially in terms of two criteria: performance (gradeability), and cost. The technologies assumed in this example have minimal influence on the gross vehicle weight. Hence, gross vehicle weight is not used for evaluating technologies. As far as the sensitivity of these technologies is concerned, the evaluation is determined by considering the first year technology as the baseline and assigning cost and performance factors to other technologies. Table 3 the shows cost and performance (gradeability) for these technologies.

Consider an example of a full forward type of cab technology. If the cab frontal is A for a full forward cab, then the area for a semi-forward cab is A/$\sqrt{2}$. As a result the gradeability is increased roughly by a factor of 1.1 for the semi-forward cab

When the manufacturer switches over from one technology to another technology, there will be a cost incurred to the manufacturer in the form of restructuring, new component sourcing, interfacing new components with existing ones, and so forth. The cost incurred is termed as the switchover cost. The switchover cost diminishes the overall profitability of the manufacturer. In this paper, we have considered three types of technology switchover cost, namely, switchover cost of engine, switchover cost of gear-box, switchover cost of vehicle cabin. Mathematically, it has been represented by the following equation:

$$\text{Switchover cost} = \sum SOC(Eng, Gb, Cab) \tag{5}$$

The switchover costs for different technologies are listed in Table 4.

2.5 Platform development cost

In this paper, we assumed that there will be six different variants across the three year planning horizon. Out of these six variants, three variants are to be manufactured in year 1, while one and two additional variants will be manufactured in years 2 and 3 respectively. Hence, there can be a maximum of six different platforms for six different product variants. However, the best scenario from ‘economies of scale’ perspective will be the one in which all the six different variants are derived from a single platform. In our problem, the possible number of platforms can be anywhere from one to six. Higher number of platforms may lead to higher platform development cost, which may lead to reduced profitability. The total platform development cost can be mathematically represented by the following equation:

$$\text{Platform development cost} = \sum_{i=1}^{N}\sum_{j=1}^{m} PDC_{ji} * Y_i \qquad (6)$$

Where PDC_{ij} is the development cost for j^{th} subsystem for platform i. The orders of numbering for subsystems and respective costs are listed in Table 5.

2.6 Detailed system/subsystems parameters

An automotive truck is a combination of various systems such as the power-train system, body system, load bearing system, and auxiliary system as shown in Figure 5. Each of these systems has different associated subsystems with specific functionalities. As an example, the engine is a key element of the power train. The engine provides the required power to the vehicle. The associated system parameters of engine are RPM, torque, and the engine horsepower. Figure 5 also depicts the general configuration of an automotive truck including associated systems and subsystems, and key design parameters.

2.7 Establishment of cost relationship

According to de Weck (2005), the cost of a product can be modeled by the following methods:

a) Bottom-up process oriented: Models the cost on the basis of individual fabrication and assembly steps.

b) Cost-estimation-relationship: Fits regression curves to historical cost of precursor products/systems.

c) Costing-by-analogy: Take a known product and its cost as a baseline reference and calculate the differential costs with respect to the reference by adjusting for changes in design variables or product options.

However, there are a few problems in modeling the cost using the above three approaches. Due to the large number of operations involved in automotive manufacture, the task of cost modeling using a bottom-up process oriented becomes intricately very difficult. Very few automobile manufacturers declare cost information of the automobile truck subsystems; hence regression curves for cost estimation cannot be employed. Non-availability of cost data is the primary reason the cost can not be modeled using costing-by-analogy technique. Considering these difficulties, the cost of individual subsystems is assumed to be a linear function of the respective parameters. All the cost coefficeints values are hypothetical in nature and listed in Table 6. It is assumed that all the manufacturing cost elements such as the production cost, operations cost, assembly cost and overheads are included in the cost coefficients.

Due to platforming there may be some performance loss of the product (truck). The additional cost incurred corresponding to the performance loss has been estimated using the general Taguchi loss function (Fowlkes and Kreveling, 1995)

For a given parameter x, the performance loss is given as

$$L(x) = k * (x - X)^2 \tag{7}$$

where x is the actual value of characteristic considered

X is the desired target value and k is the quality coefficient constant

The quality coefficient k is determined by estimating the loss A_o in dollars, when x deviates from X by Δ_o. This loss is assumed to be incurred by the manufacturer. Mathematically, this is represented as follows:

$$k=A_o/\Delta_o^2 \tag{8}$$

In this model the performance criterion considered is gradeability, which falls under the purview of *larger-the-best* scenario. Hence, only the negative deviation from desired target performance level will lead to performance loss cost.

The performance (gradeability) loss cost for product (truck) variant i is as follows:

$$C_{pli} = k_1*(HP_i - HP_{nom})^2 + K_2*(GVW_i - GVW_{nom})^2 \tag{9}$$

Where G_{nom} and GVW_{nom} are the nominal gradeability and nominal gross vehicle weight respectively.

For this problem the values of k_1 and k_2 are assumed to be \$50 and \$100 respectively.

3. Problem Environment

It is assumed that the manufacturer of automotive trucks seeks to manufacture a range of automotive trucks distributed across a planning horizon of three years. The manufacturer wishes to offer automotive trucks that range in engine horsepower from 250 HP to 400 HP and in gross vehicle weight from 20 ton to 34 ton. The manufacturer wishes to offer trucks in potential future markets as well as continue the satisfaction of current market demand.

The main aim of this research is to generate various variants specifications as close to the given variant specification in such a way that profitability to manufacturer is maximized. These product variants must satisfy minimum performance criteria. The performance criteria considered are gradeability and gross vehicle weight.

The objective function is to maximize the total profitability from present and future markets by satisfying the respective demand values and considering various costs such as selling price of individual variants, product variant cost (summation of all the subsystems costs in a automotive truck), platform development cost, and switchover cost. In this problem, the selling price has been made a function of key performance criterion i.e. gradeability and gross vehicle weight. The total variants cost is a summation of cost of the individual product variant 'C_{pi}' and corresponding performance loss cost 'C_{pli}' due to sharing. The following assumptions have been made in this paper:

a) Allowable performance is assumed to be known and is ±10%.

b) The probabilities for future market demands are known in advance.

c) The market considered here is a monopolistic market with no competition.

Figure 6 shows a generic black-box model for this problem listing the inputs, process, and outputs.

4. Problem Formulation

The objective function is formulated as maximization of profitability to the manufacturer.

Maximize (Profitability) =

$$\begin{aligned}&\sum_{i=1}^{N}\{D_i * (SP_{HP} * HP_i + SP_{GVW} * GVW_i - C_{pi} - C_{pli} - \sum_{j=1}^{m} PDC_{ij} * Y_i)\} \\ &- \sum SOC(Eng, GB, Cab)\end{aligned} \tag{10}$$

Where $C_{pi} = \sum_{j=1}^{m} C_{ji}$ C_{ji} is the cost of subsystem j for the segment i. (11)

The objective function is subject to the following constraints

a) Engineered system constraints

1) Load bearing system constraints

The gross vehicle weight of the vehicle is the algebraic sum of the front and rear axle load rating.

$$GVW_i = (X_{FaSLci} + X_{RaSLci}) \quad (12)$$

The load bearing capacity of the long members is governed by section modulus and yield strength of material. The section modulus is a function of length, depth, thickness and web width of the long member. For the purposes of design ease, a uniformly distributed load on long member has been considered in this study.

The force on the single long member = $GVW_i/2$ (13)

The force per unit length=GVW_i / $2X_{(FmL)\ i}$ (14)

The section modulus = $\{X_{(FmD)\ i}{}^3 * X_{(FmW)\ i} - (X_{(FmD)\ i} - 2X_{(FmT)\ i}{}^3 * (X_{(FmW)i} - X_{(FmTi)})\}/6 * X_{(FmD)i}$ (15)

The area on which the force acts is $X_{FmLi} . X_{FmWi}$, hence the average stress on long member = $(X_{(FmL)i} * X_{(FmW)i}) * (GVW_i/2 * X_{(FmL)i}) / \{X_{(FmD)\ i}{}^3 * X_{(FmW)\ i} - (X_{(FmD)\ i} - 2 * X_{(FmT)\ i})^3 * (X_{(FmW)\ i} - X_{(FmT)\ i})\} / 6 * (X_{FmD)\ i}$ (16)

In this model, we consider a factor of safety of 7 or more. Using these equations a range of frame dimensions are derived and listed in Table 7.

Whenever the wheels and tires are under load and rotation, the actual radius becomes approximately 85-90% of its original radius. For this case, we assume the compression to be 15%.

$$X_{Dyn\ i} = .425 * X_{(WtTid)\ i} \tag{17}$$

The selection of wheel rims and tires are subject to loads, i.e., the front and rear axle load ratings. Hence, for the selection of various tires configurations corresponding to different load ranges are listed in Table 8. This data sheet has been created on the basis of information given on commercially available Ameri-MSL data sheet (http://www.moderntiredealer.com/research/truckchrt.pdf) for all position on/off highway service.

2) Power train system constraints

The following relationship exists between the maximum and operational RPM.

$$X_{(RPMo)\ i} = (.5\text{-}.7) * X_{(RPM)\ i} \tag{18}$$

Further, the operational RPM, torque and HP of engine are related as follows:

$$X_{(HP)\ i} = (X=_{RPMo)\ i} * X_{(EngTor)\ i}) / 5252 \tag{19}$$

The stress developed in the clutch disc is a function of the engine torque and area. This relationship is illustrated by the following equation.

$$\text{Stress} = X_{(EngTor)\ i} * \sqrt{\Pi} / (X_{(ClFa)\ i})^{3/2} \tag{20}$$

For a given factor of safety, the clutch friction area can be determined using equation (18).

The engine torque, gear-box torque and clutch torque are related as follows:

$$2 * X_{(GbTor)\ i} \geq X=_{EngTor)\ i} + X_{(ClTor)\ i} \tag{21}$$

$$\text{Step value of gear-box} = (R_{GBi} - R_{GB2}) \times 100/R_{GB2} \tag{22}$$

The propeller shaft torque, gear-box torque and first gear ratio box are related as follows:

$$X_{(PsTor)\,i} \geq R_{(GB)\,i} * X_{(GbTor)i} \tag{23}$$

The fuel tank capacity is a function of gross vehicle weight and will be derived by the following empirical relationship:

$$X_{(FtC)\,i} = 150 * (1+GVW_i/16) \tag{24}$$

3) Body system constraints

For the selection of load body, the following empirical relationship has been developed.

$$X_{(LbVc)\,i} = 15 * (1+GVW_i/32) \tag{25}$$

The value of volumetric capacity has been made a function of GVW of the vehicle.

4) Auxiliary constraints

Braking torque: - It is defined as the amount of torque needed to bring the vehicle from motion to a standstill position. The braking torque is one of the important considerations in vehicle design.

The braking torque is mathematically expressed as follows:

$$BT = GVW_i * 3.14 / nr_i * 180 \tag{26}$$

The range of values for various system parameters are given in Table 9.

b) Compatibility constraints

Module compatibility: This constraint is associated with the compatibility among the physical modules. As an example, the engine, clutch, and gear-box always exist in a combined module in an automotive truck. This is mathematically represented by the following constraint:

$$Y_{Eng} + Y_{Gb} + Y_{Cl} = 3 \tag{27}$$

The steering is mounted in the cab, which means that the steering and cab has to be a combined module.

$$Y_{Cn} + Y_{Stg} = 2 \tag{28}$$

The rear and front axles with suspension, fuel tank, brakes, load body and wheels and tires are assembled with frame.

$$Y_{Fm} + Y_{Ras} + Y_{Fas} + Y_{Ft} + Y_{Br} + Y_{Lb} + Y_{Wt} = 7 \tag{29}$$

The compatibility in terms of the vehicle length is represented by the following constraint:

$$L_{Eng} + L_{Cl} + L_{Gb} + X_{PsL} + L_{Oh} \leq X_{Fm} \tag{30}$$

Figure 7 represents this constraint.

It is assumed that the overhang length is 10% of the total frame length across all the market segments.

$$L_{(Oh)\,i} = .1 * X_{(FmL)\,i} \tag{31}$$

c) Platforming constraints

For platforming of the front axle of one segment and front axle of the intermediate segment, the difference between values of two segments should be less than or equal to one ton.

$$X_{(FaSLc)\,i} - X_{(FaSLc)\,i+1} \leq 1 \tag{32}$$

Similarly, for platforming of the rear axle of one segment and rear axle of the intermediate segment, the difference between values of two should be less than or equal to one ton.

$$X_{(RaSLc)\,i} - X_{(RaSLc)\,i+1} \leq 1 \tag{33}$$

The front axle value should not exceed the rear axle value.

$$X_{(RaSLc)\,i} \geq X_{(FaSLc)\,i} \tag{34}$$

There can be a maximum of six different platforms, for each of the individual subsystems which can be represented by the following mathematical equations:

$$\sum_{i=1}^{N} Y_{(Subsys)i} \leq 6 \tag{35}$$

Subsys = Se (engine, gear-box, clutch, fuel tank, wheels and tires, propeller shaft, cabin, steering, load body, front axle, rear axle, brake, frame)

5. Solution methodology

The flow chart of the solution methodology is shown in the Figure 8. The steps involved in the solution methodology are explained below.

5.1 Identify primary and secondary parameters

The parameters of various subsystems are categorized into primary and secondary parameters. The primary and secondary parameters are described below.

Primary parameters: For this problem, primary parameters refer to those parameters which directly influence the performance criteria or those parameters which are influenced by these parameters (parameters influencing performance). For example, the engine torque and front axle load rating directly affects the gradeability and gross vehicle weight respectively. Hence, these two parameters are treated as primary parameters. However, the gear-box torque does not directly influence gradeability, but is influenced by the selection of the engine torque. Hence, the gear-box torque also falls under the purview of primary parameters.

Secondary parameters: Secondary parameters refer to those parameters that do not directly play a role in determining the performance. It is to be noted that all the secondary parameters of the subsystems do not affect the gross vehicle weight very significantly. For example, the combined weight of the propeller shaft and front axle contributes to roughly 2% of entire gross vehicle weight. Similarly, the weight of the truck cabin contributes to less than 1% of entire gross vehicle weight. All the primary and the secondary parameters are listed in Figure 8.

5.2 Perform Optimization for primary parameters

The optimization model with X as a set of primary and Y as set of secondary parameters is shown below:

Z = Min {f1(X) + g1(Y)}
Subject to
f2(X) > f2
g2(Y) >g2

This problem can be rewritten as:

Z1 = Min f1(X) Subject to f2(X) > f2	+	Z2 = Min g1(Y) Subject to g2(Y) > g2

In the similar fashion, the problem formulated in section 4 is modified to include only the primary parameters and related constraints and objective function that have been modified. Thereafter, the modified problem has been solved in Premium Solver using non-linear generalized reduced gradient (GRG). The initial solution is iterated to get successively better solutions. The solution is iterated 100 times beyond which no further improvement in the objective function is found. The derived values of the primary parameters for all six different variant are listed in Table 10.

5.3 Perform Optimization for secondary parameters

The problem formulated in section 4 is modified to include only the secondary parameters and related constraints and objective function have been modified. The values of the secondary parameters for the variants are listed in Table 11.

5.4 Determine individual product variant cost

After obtaining the values of the primary and secondary parameters, the cost corresponding to each of the subsystem is calculated to determine the actual vehicle cost for each of the vehicle variant. The individual subsystem cost, total vehicle cost, selling price per unit, and profitability per unit for each of the variant are listed in Table 12.

5.5 Identify criteria for platforming

The criteria used to determine whether to opt for platforming or individual design is explained in this section. If the total cost of the individual variant and individual platform (along with demand consideration) is more than total cost of variant from a platform and corresponding platform development cost (along with the demand consideration), then only platforming is preferred otherwise individual design is preferred. For example, the engine and the gear box have been preferred for complete individual design, while the rest of the subsystem will be developed from a number of common platforms. Further, if the values of the parameter for different variants come out to be the same, then the less expensive platform will be chosen for development. The mathematical average will be considered as the platform value for different individual variants parameters value for the systems whose difference is less than 10% of the lesser value. Table 13 lists the platforms for the engine, gear-box, front and rear axle. Table 13 also provides information about subsystem platforms used by different variants.

5.6 Calculate the variant cost and performance loss cost from platform

In this section, the cost for different subsystem platform is determined. The performance loss cost in term is also determined. The performance loss cost is summation of performance loss due to deviation from nominal gross vehicle weight and nominal engine horse power. Table 14 and Table 15 list the variant cost from platform and performance loss cost respectively.

5.7 Determine the total profitability

In this section, the total profitability corresponding to each of the variant is determined. The profitability of a variant is the function of the selling price of the variant, cost of the total subsystem, performance loss cost and cost of the corresponding platforms for different subsystems. These are listed in Table 16.

5.8 Develop the platform architecture

In this study, the engine, clutch, gear-box, propeller shaft, rear axle with suspension, front axle with suspension, steering, and brake are assumed to be modular systems, while the rest are assumed to be scalar systems. It is assumed that this information is known *a priori*. Platform architecture suggests which subsystem platforms serve as the basis for the subsystem specification. For example, all six different types of engines corresponding to different variants are derived from six different engine platforms. Consider the example of cab in which four different cab specifications are derived from a single platform and the remaining two cab specifications are derived from a different platform. Figure 10 provides the overall platform architecture for the automotive trucks.

6. Results and Discussion

Refer to Tables 11 and 12. The results indicate that the selection of individual subsystem configuration is contingent upon the engine toque, front axle load rating, rear axle load rating, and dynamic tire radius. Engine torque influences the selection of the overall power-train system, while the front and rear axle load rating affects the selection of load bearing and body system. For the first variant the engine, rear axle, and front axle configurations are Eng1, Ra1, and Fa1 respectively. Due to the engine configuration Eng1, the configuration of gear-box and clutch are Gb1 and Cl1 respectively. In case of the second variant, due to the higher gradeability requirement, the engine torque has increased leading to a different specification for the gear-box and clutch configuration

Refer to Table 13. There are three and five different platforms for the front and rear axle, which leads to five different gross vehicle weight combinations for a total of six different variants. Hence, there should be five different specifications for the brake, load body, and fuel tank. But only three different platforms for these subsystems exist. This is due to the fact that the brake, load body and fuel tank do have very negligible effect on the overall performance requirement, i.e., engine horse power and gross vehicle weight. Hence, the brake, load body, and fuel tank has been developed from platforms having lower development cost. However, even for subsystems which do not affect the performance, certain criteria (which reflects the technical constraint for that subsystem with the rest of the system) is considered for platformability. An example of this criteria is that only those subsystems which are within 10% difference of their nominal values can be platformed.

Refer to Table 15. Even though the engine for the specification of the entire six variants is based on the individual design, there are some performance losses in case of variants V1.3, V2.1, V3.1, and V3.2. This is due to the fact that the engine specification is governed by the design constraint. The design constraint in this case is the minimum gradeability requirement. Hence, this establishes the fact that adhering to individual design does not always necessarily lead to any performance loss.

All the scalar subsystems are assumed to be derived from the respective subsystem platform. For example, the frame length, depth, width and thickness will be scaled to suit different variant requirements. Hence, the platform of the long member the shape of the section remains the same while values of four variables, i.e., the frame length, depth, width and thickness, change. The section of frame chosen in this case of the product family is shown in Figure 11.

Refer to Table 17. It is to be noted that sharing of various subsystems across different variants is heterogeneous in nature.

7. Conclusions and Future Work

The major contribution of this study is the introduction of new engineered system case example to the existing product platform literature. The engineered system has been decomposed into various interacting subsystems which are defined by the primary and secondary design parameters. These interacting subsystems possess interrelations in terms of various mathematical relationships amongst them. The cost of the individual subsystem is modeled in terms of the cost of the coefficients of respective parameters.

The product family example considered in this paper is associated with a dynamic market with changing product specifications over a given horizon (three years). The demand for the future market has been estimated by assigning probabilities of expansion to potential future market spaces. The cost and selling price of individual product, respective platform development cost, technology switch over cost, and performance cost has been considered for the total profitability calculations. The cost of individual products has been expressed as the summation of all the subsystem it comprises and the selling price has been made a function of overall specifications (engine horsepower and gross vehicle weight) of the product.

One of the assumptions made in this paper is that the manufacturer also continues to offer products in future market spaces in addition to the current market space. Hence, the product obsolence issue has not been considered. Also, one of the limitations of this paper is that, it does not consider market competition and model is built for a single manufacturer. However, the factors reflecting competition can be incorporated in the future to make the model more comprehensive and realistic.

The subsystems mentioned in this paper can be further drilled down to make a case for detailed-design optimization. An obvious extension of the example case problem would be the refinement of cost relationships. More detailed manufacturing activities and their associated cost can be included to make the problem more realistic.

ACKNOWLEDGEMENTS

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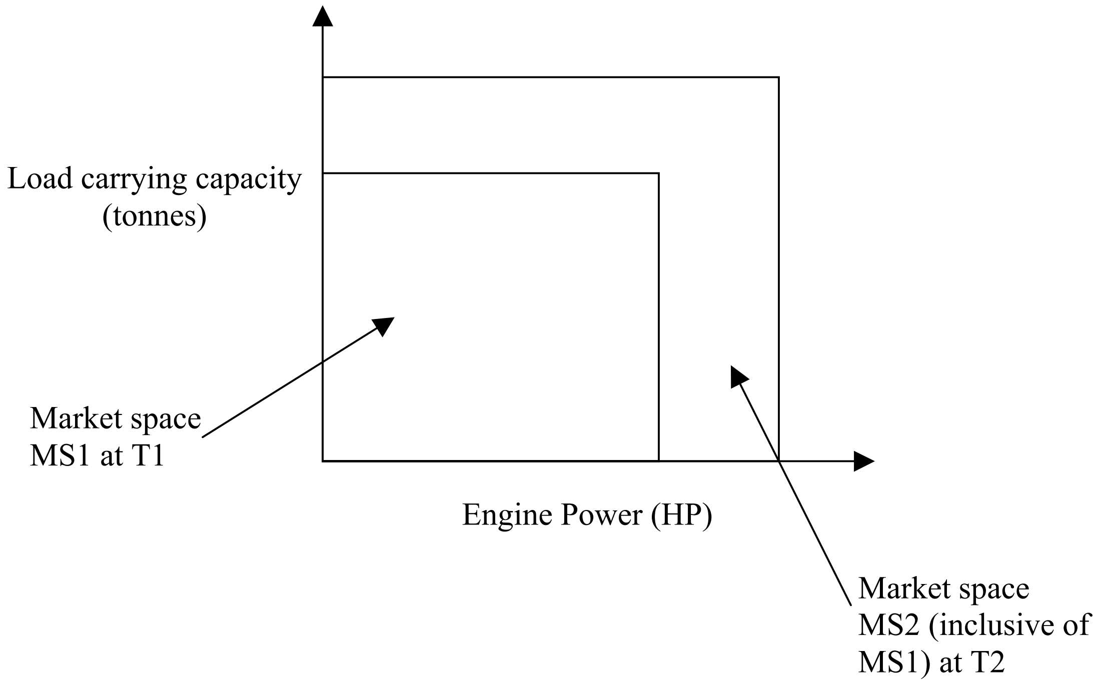

Figure 1: Market spaces of automotive trucks

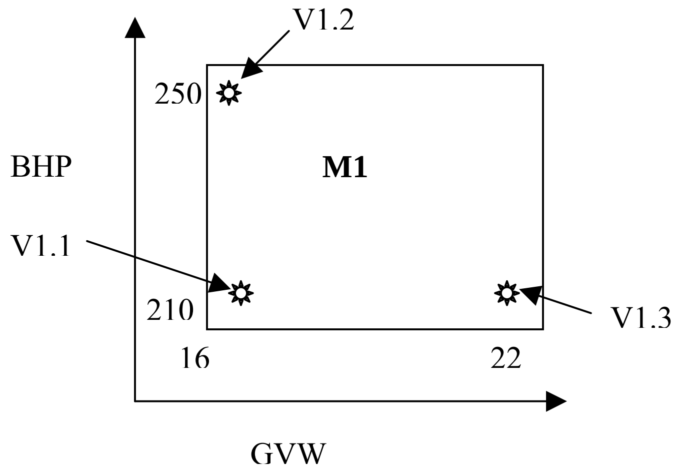

Figure 2: Current market space

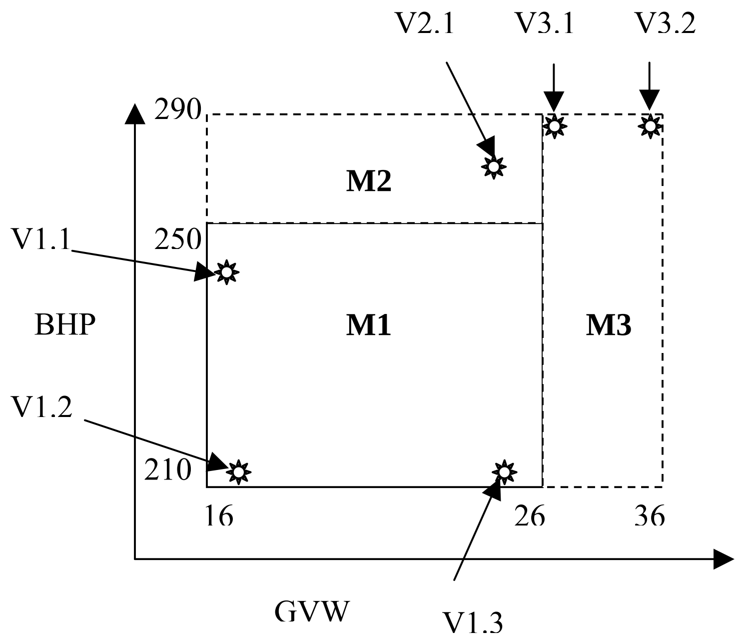

Figure 3: Consolidated current and future market space

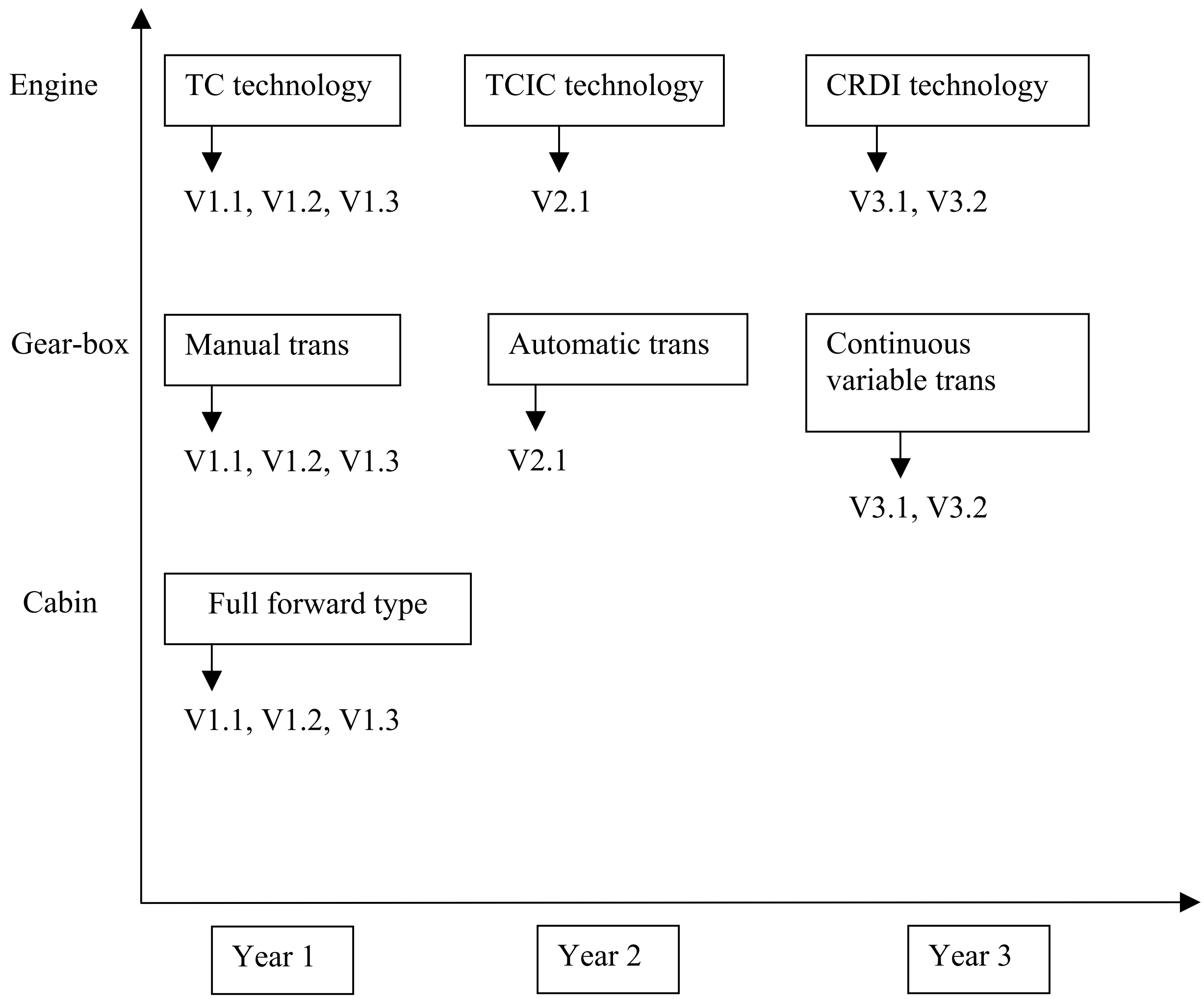

Figure 4: Technology roadmap for automotive truck example

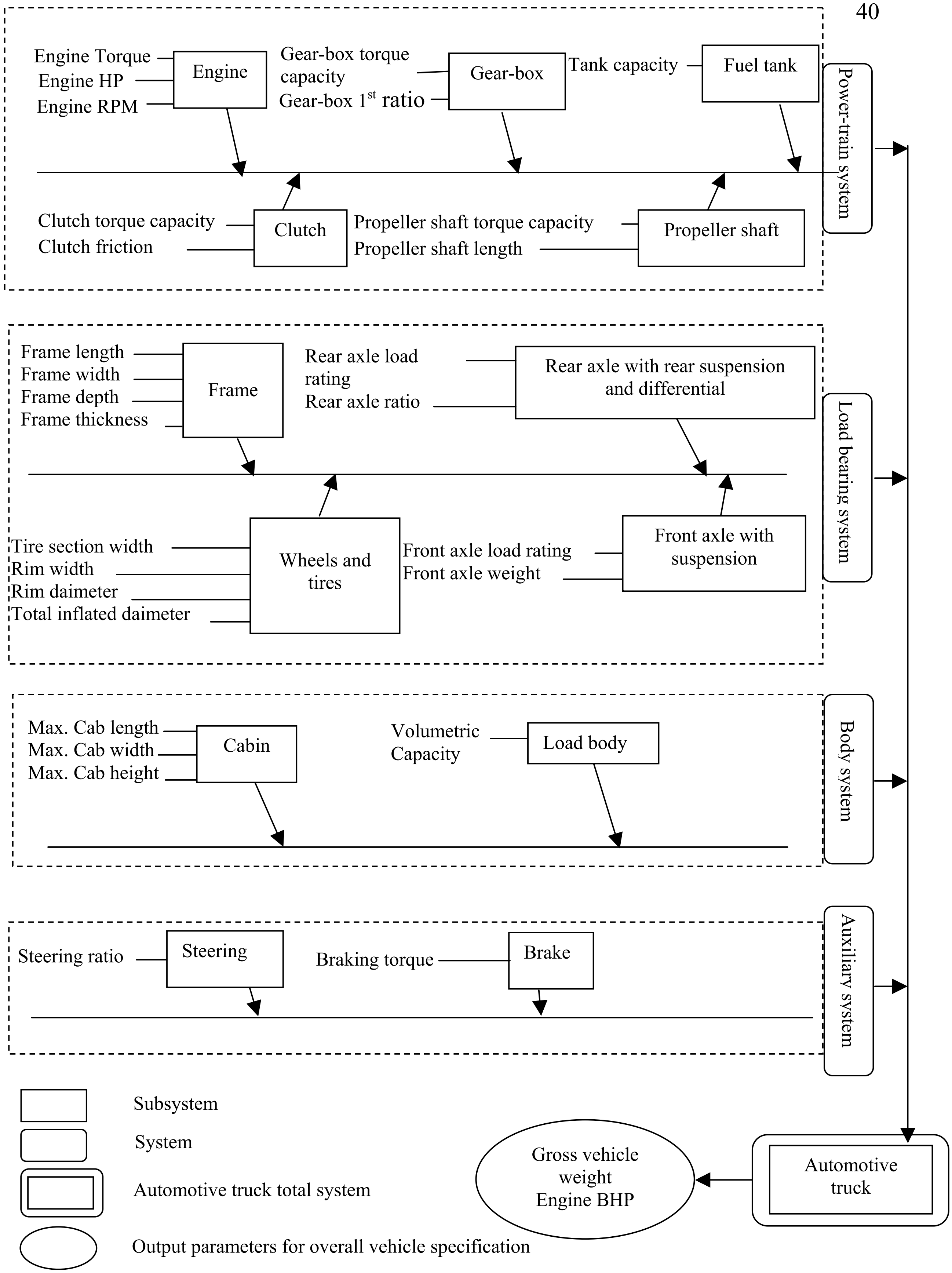

Figure 5: System, subsystems and design parameters

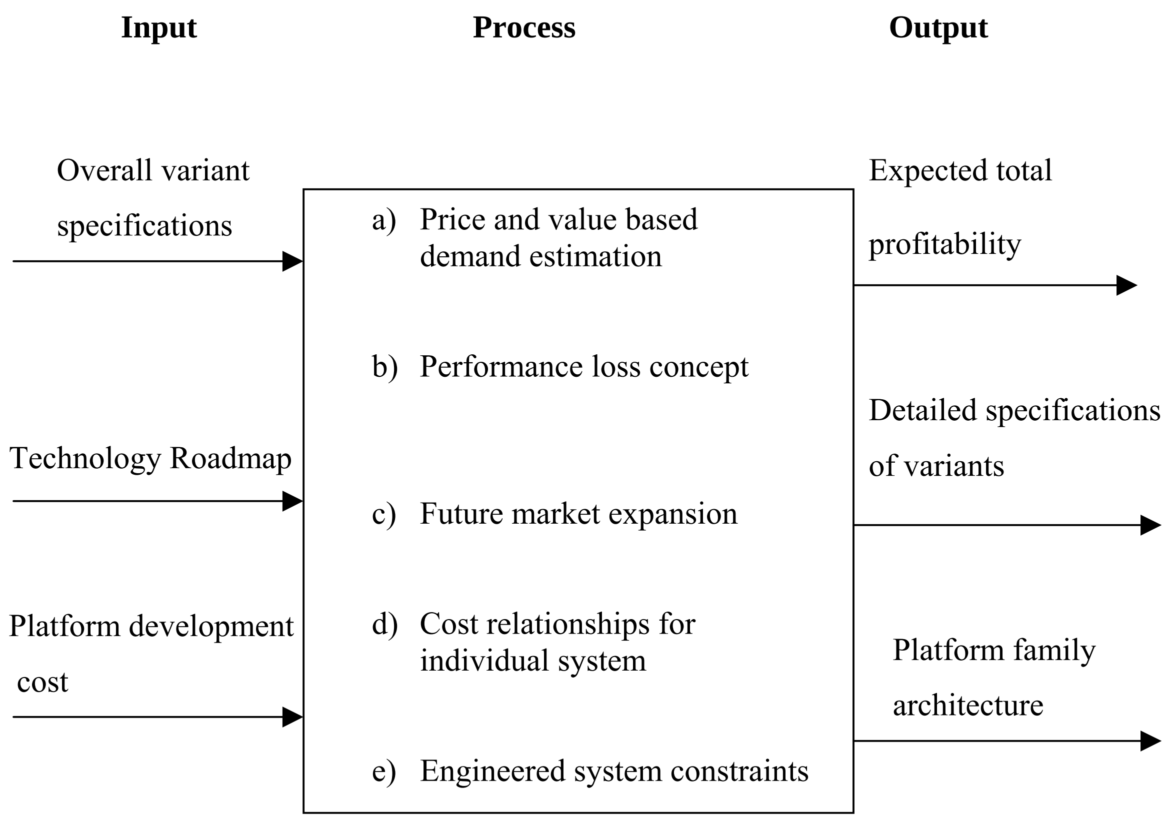

Figure 6: Black box model for the problem

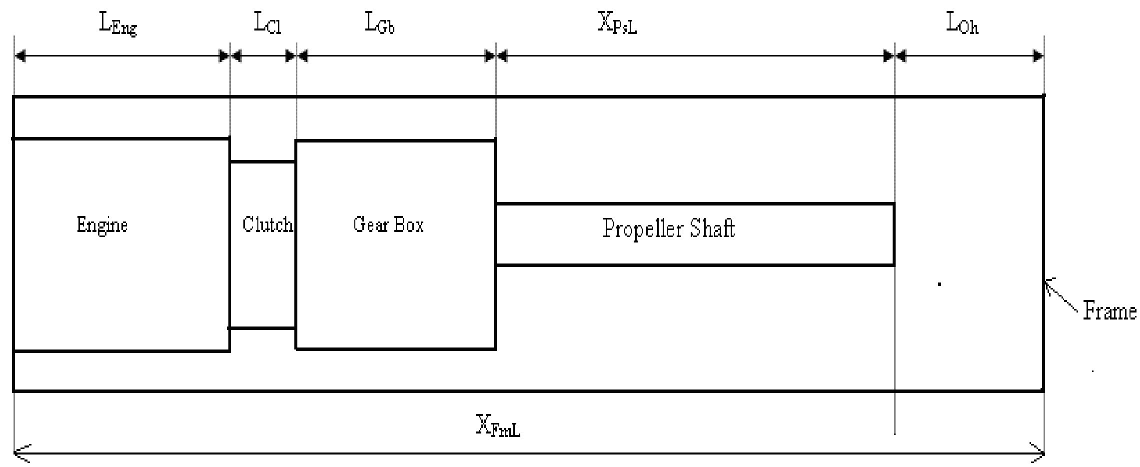

Figure 7: Establishing length relationship

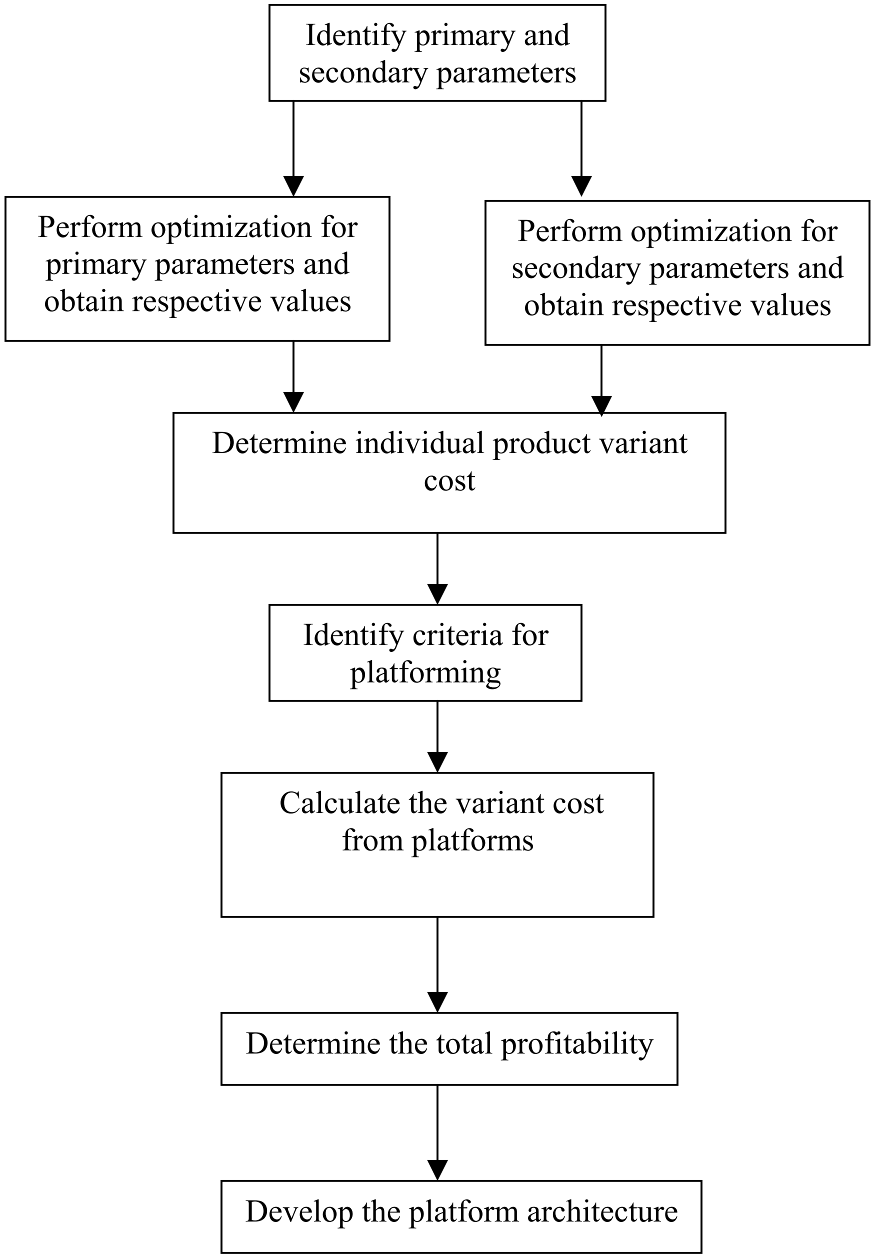

Figure 8: Flow chart of the solution methodology

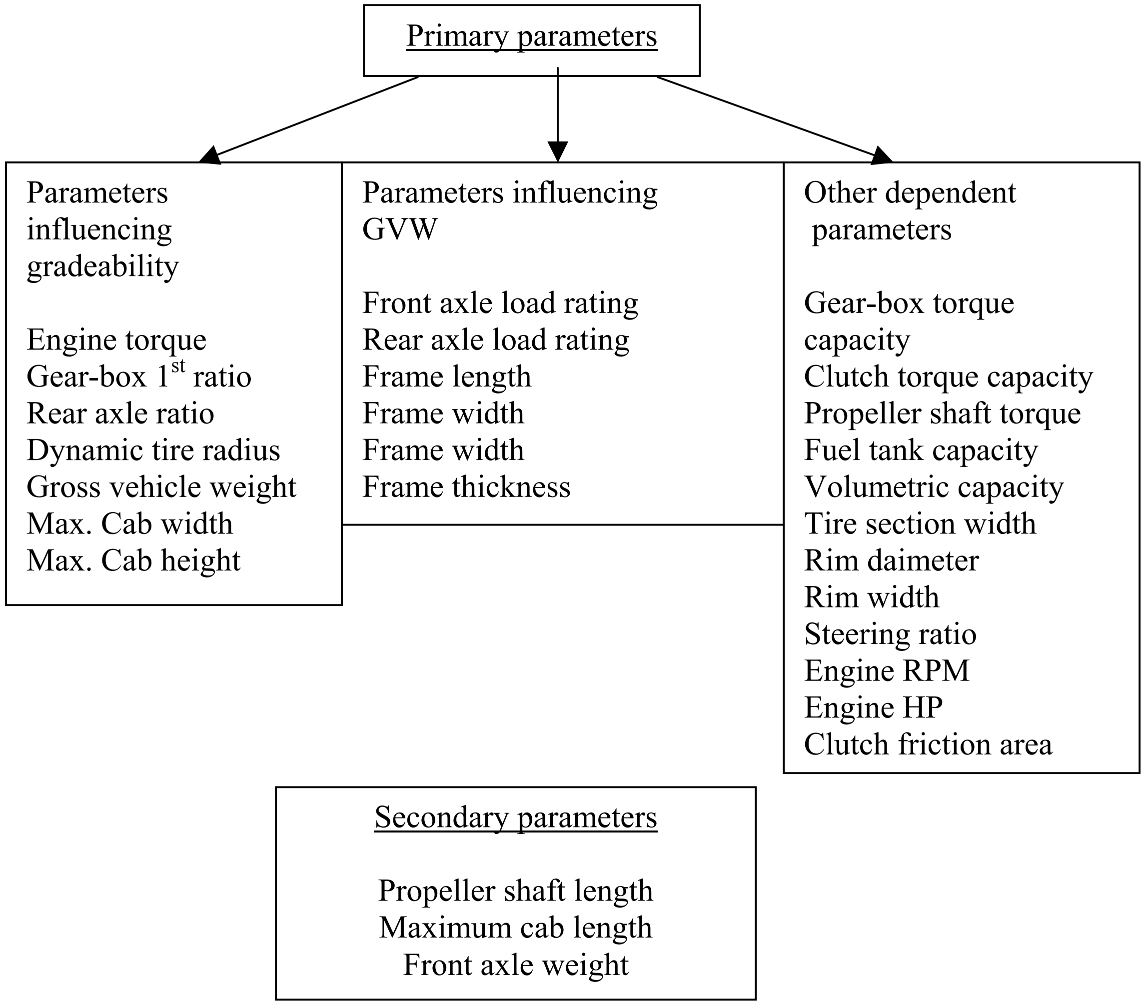

Figure 9: Primary and Secondary parameters

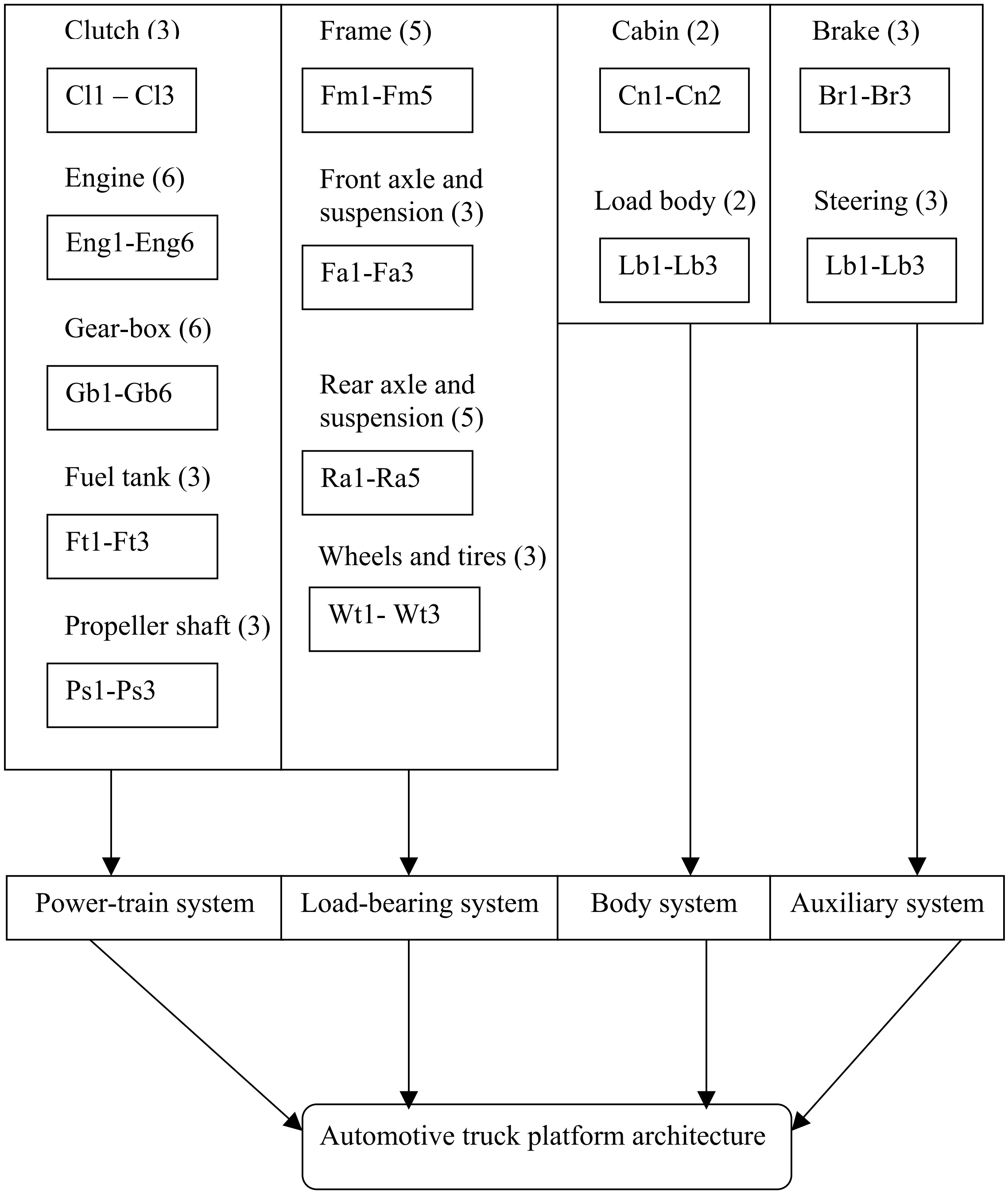

Figure 10: Automotive truck platform architecture

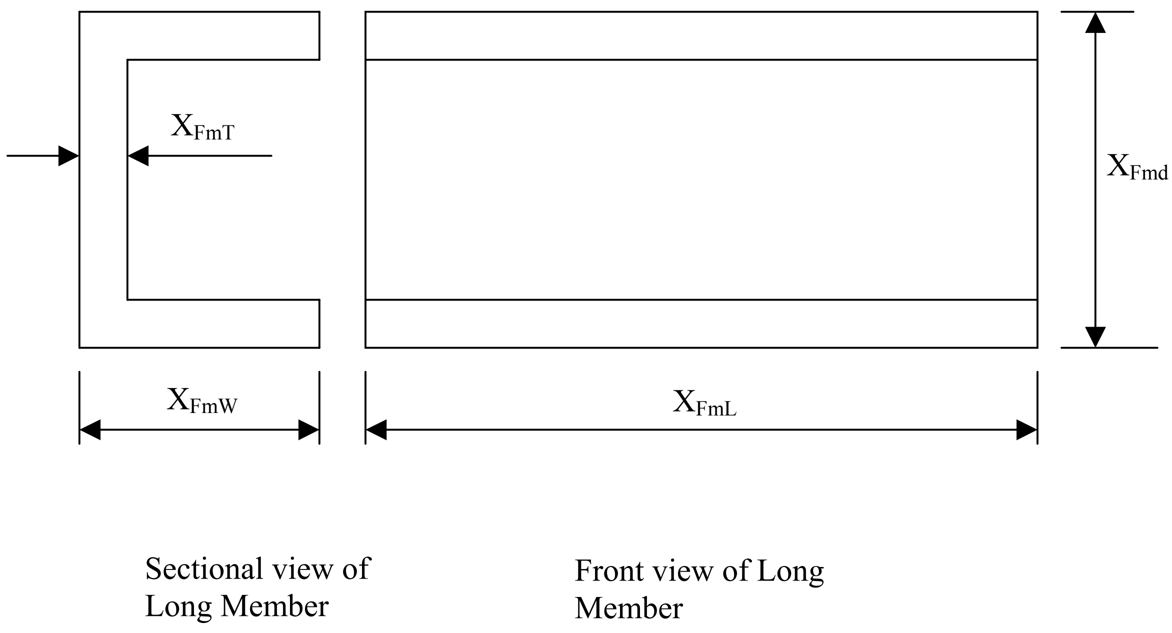

Figure 11: Dimensional details of long member

Table 1: Product variants in current market space

No.	Product Variant(s)	Nominal gradeability (%)	Engine horse power (HP)	Gross vehicle weight (tonnes)	Demand(units/per year)
1	V1.1	45	250	20	19,000
2	V1.2	54	270	22	20,680
3	V1.3	36	270	26	22,280

Table 2: Product variants in future market space

Market Space	Product Variant	Nominal gradeabilit y (%)	Engine horse power (HP)	Gross vehicle weight (tonnes)	Probability	Proba bility (Varia nt)	Probability (market space U variant)	Demand
M2	V2.1	46	320	26	.5	1	.5	22,240
M3	V3.1	37	320	34	.5	.5	.25	9,688
	V3.2	40	400	34	.5	.5	.25	10,920

Table 3: Technology comparison in terms of cost and performance (gradeability)

Technology type	**Cost factor**	**Performance(gradeability)**
TC	1	1
TCIC	1.1	1.1
CRDI	1.2	1.2
Manual transmission	1	1
Automatic transmission	1.1	1.05
Continuous variable transmission	1.15	1.1
Full forward type	1	1
Semi forward type	1.1	1.1

Table 4: Switchover cost

Switchover	**Switchover cost ($)**
TC to TCIC	80, 000
TCIC to CRDI	100, 000
Manual to automatic transmission	80, 000
Automatic to continuous variable transmission	100, 000
Full forward to semi forward type	120, 000

Table 5: Platform development cost

Subsystems	Denomination (j)	Platform development cost ($)					
		1	2	3	4	5	6
Engine	1	300,000	375,000	450,000	600,000	750,000	900,000
Gear-box	2	200,000	250,000	300,000	400,000	500,000	600,000
Clutch	3	100,000	125,000	150,000	200,000	250,000	300,000
Front axle	4	200,000	250,000	300,000	400,000	500,000	600,000
Rear axle	5	200,000	250,000	300,000	400,000	500,000	600,000
Fuel tank	6	100,000	125,000	150,000	200,000	250,000	300,000
Propller shaft	7	100,000	125,000	150,000	200,000	250,000	300,000
Frame	8	300,000	375,000	450,000	600,000	750,000	900,000
Wheel and tires	9	100,000	125,000	150,000	200,000	250,000	300,000
Cabin	10	100,000	125,000	150,000	200,000	250,000	300,000
Brake	11	100,000	125,000	150,000	200,000	250,000	300,000
Steering	12	100,000	125,000	150,000	200,000	250,000	300,000
Load body	13	100,000	125,000	150,000	200,000	250,000	300,000

Table 6: Cost coefficients for subsystems

Subsystems	Parameters	Manufacturing cost coefficients	Cost relationship
Engine	HP RPM(Maximum) Eng Torque	C_{HP} = \$15/HP. C_{RPM} = \$2/RPM C_{Engtor} = \$4/Nm	C_{Engine} = (C_{HP}.HP + C_{RPM} .RPM + C_{Engtor} .Engtor)
Gear-box	GB torque capacity GB 1st ratio	C_{GBtor} = \$4/Nm $C_{1stratio}$= \$500/single ratio	C_{GB} = (C_{Gb}.Gb torque + $C_{1stRatio}$. Step)
Clutch	Clutch torque capacity Friction area	C_{Cltor} = \$2/Nm C_{Flarea} = \$.3/cm^2	C_{Clutch} = (C_{Cltor}.Cltor + C_{Flarea}.Fl area)
Propller shaft	Ps torque Ps length	C_{Pstor} = \$.1/Nm $C_{Pslength}$ = \$55/m	$C_{Pslength}$ =($C_{Pslength}$.Pslength + C_{Pstor}.Pstor)
Frame	Frame length Frame depth Frame Width Frame thickness	C_{FmL} = \$.2/mm C_{FmD} = \$5/mm C_{FmW} = \$15/mm C_{FmT} = \$215/mm	C_{Frame} = (C_{FmL}.FmL + C_{FmD}.FmD + C_{FmW}.FmW+ C_{FmT}.mT)
Rear axle	Rear axle load rating Rear axe ratio	C_{Ralr} =\$850/tonnes $C_{Raratio}$ = \$660/single unit ratio	C_{Ra} = (C_{Ralr}.Ralr + $C_{Raratio}$.Raratio)
Front axle	Front axle load rating Front axle weight	C_{Falr} = \$900/tonnes C_{Faw} = \$ 2000/tonnes	C_{Falr} = (C_{Falr}.Falr + C_{Faw}.Faw)
Wheels and tires	Tyre section width Rim width Rim daimeter Dynamic tyre radius	$C_{tiresecwidth}$ = \$.2/mm $C_{rimwidth}$ = \$.3/mm C_{rimdai} = \$.1/mm C_{dynrad} = \$.15/mm	$C_{W\&T}$ = ($C_{tiresecwidth}$.Tire section width + $C_{rimwidth}$.Rimwidth + C_{rimdai}.Rim dai + C_{dynrad}.Dyn rad)
Fuel tank	Fuel tank capacity	C_{Ftc} = \$4.5/lit	C_{Ftc} = C_{FtC}.Ftc
Load body	Load body capacity	C_{Lbvc} = \$160/m^3	Clbvc = C_{lbvc} .Lbvc
Steering	Steering ratio		C_{str} = \$(172.38 . str – 1136.25)
Cabin	Cabin Length Cabin width Cabin height	C_{CabL} = \$750/m C_{CabW} = \$540/m C_{CabH} = \$870/m	C_{cab} = C_{cabL}.CabL + C_{CabW}.CabW + C_{CabH}.CabH
Brakes	Braking torque	C_{Brator} = \$.1/Nm	C_{Brake} = C_{Brator} .Braking torque

Table 7: Frame dimensions

Frame dimension	1	2	3	4
Frame length (mm)	7000-7600	7600-8300	8300-9000	8300-9000
Frame depth (mm)	280-290	290-300	300-310	300-310
Frame web width (mm)	90-100	100-110	110-120	110-120
Frame thickness (mm)	7-7.5	7.5-8	8-8.5	8-8.5
Stress in frame (N/mm^2)	29.2-30.9	29.8-30.9	30.9-31.1	30.9-31.1
Yield strength of material (N/mm^2)	250	250	300	300
Factor of safety	8.09-8.56	7.5-7.86	7.6-8.0	7.34-7.81
GVW (Ton)	18-20	20-22	22-26	26-34

Table 8: Tire details (Single tire)

Load capability (kg)	**Wheels and tires dimensions**			
	Section width (mm)	**Rim diameter (mm)**	**Rim width (mm)**	**Total inflated diameter (mm)**
3000-3250	320-335	610-618	210-216	1120-1141
3250-3500	335-360	618-625	216-223	1141-1164
3500-4000	360-375	625-633	223-230	1164-1188
4000-5000	375-390	633-640	230-238	1188-1211
5000-6000	390-410	640-655	238-250	1211-1230
6000-7500	410-420	655-665	250-260	1230-1245
7500-8000	440-450	670-685	270-285	1260-1275

Table 9: Range of system parameter values for each variant corresponding to different range of GVW

System parameters	**1**	**2**	**3**	**4**
Engine Torque (Nm)	750-900	840-965	1030-1240	1200-1400
Engine RPM	1470-1750	1470-1770	1470-1785	1470-1720
Gear box first ratio	8.0-9.5			
Front axle weight (Tonnes)	.185-.2	.185-.2	.215-.23	.23-.245
Rear axle ratio	5-6			
Dynamic tire radius (mm)	475-490	475-490	500-515	510-525
Steering ratio	20-23	20-23	23-27	24-28
Propeller shaft length (m)	2.8-3.08	2.8-3.08	3.38-3.62	3.66-3.90
Maximum cab length (m)	1.71-1.74	1.71-1.74	2.2-2.38	2.5-2.64
Maximum cab width (m)	2.4-2.48	2.4-2.48	2.55-2.68	2.6-2.72
Maximum cab height (m)	1.5-1.56	1.5-1.56	1.70-1.82	1.80-1.86
GVW (Ton)	18-20	20-22	22-26	26-34

Table 10: Primary parameter values for each variant

Sl No	Parameters (Dependent)	Variants					
		V1.1	V1.2	V1.3	V2.1	V3.1	V3.2
1	X_{EgTor} (Nm)	893	963	961	1133	1114	1400
2	X_{RPMo}	1470	1470	1470	1470	1470	1470
3	X_{Hp}	250	270	268	317	311	392
4	R_{GB}	9.5	9.5	9.5	9.5	9.5	9.5
5	X_{FaSlC} (tonnes)	10	10	12	12	17	17
6	X_{RaSlC} (tonnes)	11	12	14	14	17	17
	X_{Cwpr}	6	6	6	6	6	5.05
8	X_{FmL} (mm)	7500	7600	7950	7950	9233	9233
10	$X_{FmD\,(}$mm)	288	290	295	295	313	313
11	X_{FmW} (mm)	98	100	105	105	123	123
12	X_{FmT} (mm)	7.4	7.5	7.75	7.75	8.67	8.67
13	X_{FtC} (litres)	346.875	356.25	375	375	468.75	468.75
14	X_{LbVc} (m^3)	24.84	25.31	26.25	26.25	30.94	30.94
15	X_{StgSr}	22.5	23	23.5	23.5	26.5	26.5
17	X_{ClTor} (Nm)	893	963	961	1133	1114	1400
18	X_{PSTor} (Nm)	8485.37	9146	9126	10767	10579	13300
19	X_{Dyn} (mm) Rear	475	475	485	485	495	495
20	X_{WtSw} (mm) Rear	320	320	335	335	360	360
21	$X_{WtRw,}$ (mm)Rear	210	210	216	216	223	223
22	X_{WtRd} (mm) Rear	610	610	618	618	625	625
23	K	4	4	4	4	4	4
24	X_{Dyn}(mm)Front	494	494	514	514	523	523
25	X_{WtSw} (mm) Front	360	360	390	390	410	410
26	$X_{WtRw,}$ (mm) Front	223	223	238	238	250	250
27	X_{WtRd}, (mm) Front	625	625	640	640	655	655
28	L	2	2	2	2	2	2
29	X_{ClFa} (cm^2)	1850	1947	1944	2170	2146	2500
30	X_{BrTor} (Nm)	7.1×10^4	7.42×10^4	8.95×10^4	8.6×10^4	11.9×10^4	11.9×10^4
31	X_{CnW}(m)	2.4	2.4	2.46	2.46	2.55	2.55
32	X_{CnH}(m)	1.5	1.5	1.6	1.6	1.7	1.7

Table 11: Secondary parameter values for each segment

Sl. No.	System parameters (Independent)	Variants					
		V1.1	V1.2	V1.3	V2.1	V3.1	V3.2
1	X_{PsL}(m)	2.8	2.8	3.16	3.16	3.38	3.66
2	X_{CnL}(m)	1.71	1.71	1.80	1.80	2.2	2.5
3	X_{FaW}(Ton)	.2	.2	.215	.215	.23	.245

Table 12: Individual subsystem and variant cost

Sl. No.	Subsystems	Variant Cost					
		V1.1	V1.2	V1.3	V2.1	V3.1	V3.2
1	Engine	10262	10842	10804	12227	12061	14420
2	Clutch	2341	2510	2505	2917	2872	3550
3	Gear box	8014	8154	7113	7727	7853	7852
4	Propeller shaft	749	823	857	981	1076	1192
5	Frame	6000	6000	6729	6729	7486	8243
6	Front axle with suspension	8900	8900	10630	10630	14910	14910
7	Rear axle with suspension	13860	14760	16560	16560	19260	18633
8	Cab	3883	3883	4070	4070	4506	4506
9	Load body	3975	4050	4200	4200	4950	4950
10	Steering	2741	2827	2914	2914	3431	3431
11	Brakes	7082	7419	8953	8953	11949	11949
12	Fuel tank	1561	1603	1687	1687	2109	2109
13	Wheels and tires	1379	1379	1449	1449	1507	1507
Total vehicle cost		24253	30248	32929	57356	44430	58748
Selling price per unit		95000	103400	111400	122400	138400	156000

Table 13: Platform details for different subsystems

Subsystems	Parameters	Platforms						Platform variant information
Engine		Eng 1	Eng2	Eng3	Eng4	Eng5	Eng6	Variant 1, 2, 3, 4, 5, 6 derived from Platform 1, 2, 3, 4, 5, 6 respectively
	Engine torque (Nm)	893	963	961	1133	1114	1400	
	RPM (Operational)	1470	1470	1470	1470	1470	1470	
	Horse power (HP)	250	270	268	317	311	392	
Gear-box		Gb1	Gb2	Gb3	Gb4	Gb5	Gb6	Variant 1, 2, 3, 4, 5, 6 derived from platform 1, 2, 3, 4, 5, 6 respectively
	Gear Box torque (Nm)	893	963	961	1133	1114	1400	
	Gear box 1st ratio	9.5	9.5	9.5	9.5	9.5	9.5	
Front axle		Fa1	Fa2	Fa3	Variant (1,2), (3,4), (5,6) derived from Platform 1, 2, 3 respectively			
	Front axle load rating (ton)	10	12	17				
	Front axle weight (kg)	.2	.215	.23				
Rear axle		Ra1	Ra2	Ra3	Ra4	Ra5	Variant 1, 2, (3,4), 5, 6 derived from Platform 1, 2, 3, 4, 5 respectively	
	Rear axle load rating (ton)	11	12	14	17	17		
	Rear axle ratio	6	6	6	6	5.05		
Frame		Fm1	Fm2	Fm3	Fm4	Fm5	Variant 1, 2, 3, 4, (5,6) derived from Platform 1, 2, 3, 4, 5 respectively	
	Frame length (mm)	7500	7600	7950	8125	9233		
	Frame depth (mm)	288	290	295	297.5	313		
	Frame width (mm)	98	100	105	107.5	123		
	Frame thickness (mm)	7.4	7.5	7.75	7.9	8.67		
Fuel tank		Ft1	Ft2	Ft3	Variant (1,2), (3,4), (5,6) derived from Platform 1, 2, 3respectively			
	Fuel tank capacity (liters)	356.56	380	468.75				
Wheels and tires		Wt1	Wt2	Wt3	Variant (1,2), (3,4), (5,6) derived from Platform 1, 2, 3 respectively			
	Dynamic tire radius (mm)	475	485	495				
	Tire width (mm)	320	335	360				
	Rim diameter (mm)	610	618	625				
	Rim width (mm)	210	216	223				

Table 13: Platform details for different subsystems…contd.

Propeller shaft		**Ps1**	**Ps2**	**Ps3**	Variant (1,2,3), (4,5), 6 derived from Platform 1, 2, 3 respectively
	Propeller shaft torque (Nm)	8920	10673	13300	
	Propeller shaft length (m)	2.92	3.38	3.66	

Table 14: Cost of platforms

Subsystem Platform	Eng1	Eng2	Eng3	Eng4	Eng5	Eng6
Cost ($)	10,262	10,842	10,804	12,227	12,061	14,420
Subsystem Platform	Gb1	Gb2	Gb3	Gb4	Gb5	Gb6
Cost ($)	8,322	8,602	8,594	9,282	9,206	10,350
Subsystem Platform	Fa1	Fa2	Fa3			
Cost ($)	9,400	11,230	15,760			
Subsystem Platform	Ra1	Ra2	Ra3	Ra4	Ra5	
Cost ($)	13,310	14,160	15,860	18,410	17783	
Subsystem Platform	Fm1	Fm2	Fm3	Fm4	Fm5	
Cost ($)	6,001	6,082	6,306	6,423	7,120	
Subsystem Platform	Ft1	Ft2	Ft3			
Cost ($)	1,605	1,710	2,110			
Subsystem Platform	Wt1	Wt2	Wt3			
Cost ($)	259	266	275			
Subsystem Platform	Ps1	Ps2	Ps3			
Cost ($)	1,53	1,253	1,534			
Subsystem Platform	St1	St2	St3			
Cost ($)	2,85	2,98	3,432			
Subsystem Platform	Lb1	Lb2				
Cost ($)	4,026	4,950				
Subsystem Platform	Cl1	Cl2	Cl3			
Cost ($)	2,452	2,894	3,550			
Subsystem Platform	Br1	Br2	Br3			
Cost ($)	7,260	8,775	11,190			
Subsystem Platform	Cn1	Cn2				
Cost ($)	3976.95	4575				

Table 15: Performance loss cost for variants

Variants	Performance loss cost ($)
V1.1	0
V1.2	0
V1.3	200
V2.1	550
V2.2	4050
V2.3	3200

Table 16: Profitability for each variant

Cost elements	Cost ($)					
	V1.1	V1.2	V1.3	V2.1	V3.1	V3.2
Engine	10,262	10,842	10,804	12,227	12,061	14,420
Gear-box	8,322	8,602	8,694	9,282	9,206	10,350
Front axle	9,400	9,400	11,230	11,230	15,760	15,760
Rear axle	13,310	14,160	15,860	15,860	18,410	17,783
Frame	6,001	6,082	6,306	6,423	7,120	7,120
Fuel tank	357	357	380	380	469	469
Wheels and tires	1,555	1,555	1,598	1,598	1,654	1,654
Propeller shaft	1,053	1,053	1053	1235	1,235	1,534
Steering	2,785	2,785	2,798	2,798	3,432	3732
Load body	4,026	4,026	4,026	4,026	4,950	4,950
Clutch	2,453	2,452	2,452	2,984	2,984	3,550
Brake	7,260	7,260	8,775	8,775	11,190	11,190
Cabin	3,977	3,977	3,977	3,977	4,576	4,576
Performance loss	0	0	200	550	4,050	3200
Selling price						
Total platform development cost ($1000's)	300	300	350	400	450	450
Total Profitability ($1,000,000's)	460.25	638	740.4	912.67	399.7	607.9

Table 17: Subsystem architecture commonality

<table>
<tr><td colspan="9">Variants</td></tr>
<tr><td>V1.1</td><td>V1.2</td><td colspan="2">V1.3</td><td colspan="2">V2.1</td><td>V3.1</td><td colspan="2">V3.2</td></tr>
<tr><td>Engine 1</td><td>Engine 2</td><td colspan="2">Engine 3</td><td colspan="2">Engine 4</td><td>Engine 5</td><td colspan="2">Engine 6</td></tr>
<tr><td>Gear-box 1</td><td>Gear-box 2</td><td colspan="2">Gear-box 3</td><td colspan="2">Gear-box 4</td><td>Gear-box 5</td><td colspan="2">Gear-box 6</td></tr>
<tr><td colspan="2">Front axle1</td><td colspan="4">Front axle 2</td><td colspan="3">Front axle 3</td></tr>
<tr><td>Rear axle 1</td><td>Rear axle 2</td><td colspan="4">Rear axle 3</td><td>Rear axle 4</td><td colspan="2">Rear axle 5</td></tr>
<tr><td>Frame 1</td><td>Frame 2</td><td colspan="2">Frame 3</td><td colspan="2">Frame 4</td><td colspan="3">Frame 5</td></tr>
<tr><td colspan="2">Fuel tank 1</td><td colspan="4">Fuel tank 2</td><td colspan="3">Fuel tank 3</td></tr>
<tr><td colspan="2">Wheels/tires 1</td><td colspan="4">Wheels/tires 2</td><td colspan="3">Wheels/tires 3</td></tr>
<tr><td colspan="6">Propeller shaft 1</td><td colspan="2">Propeller shaft 2</td><td>Propeller shaft 3</td></tr>
<tr><td colspan="3">Steering 1</td><td colspan="3">Steering 2</td><td colspan="3">Steering 3</td></tr>
<tr><td colspan="6">Load-body 1</td><td colspan="2">Load-body 2</td><td>Load-body 3</td></tr>
<tr><td colspan="3">Brake 1</td><td colspan="3">Brake 2</td><td colspan="3">Brake 3</td></tr>
<tr><td colspan="6">Cabin 1</td><td colspan="2">Cabin 2</td><td>Cabin 3</td></tr>
<tr><td colspan="5">Clutch 1</td><td colspan="3">Clutch 2</td><td>Clutch 3</td></tr>
</table>

VITA

Mohit Goswami was born at Jamshedpur, India on November 24, 1982. He completed his Bachelors of Technology in Manufacturing Engineering from National Institute of Foundry and Forge Technology. He completed his Masters in Engineering Management from Missouri University of Science and Technology in February 2008.