On the Meta-Modelling of Light-Duty Cordless Drill for Flexible Platform Decision Support

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Abstract
Product platform strategy has been extensively employed by leading manufacturers to economically provide market coverage. Power tool providers, such as Black & Decker and Bosch, are also beneficial from commonizing platform components across their product series. Following the research of the optimization model of platform commonality proposed in the authors' previous research, this paper develops a full set of meta-models for rated output torque and total production cost as functions of selected key design variables and drill components. An example of light-duty cordless drill is broken down into components and parameters through reverse engineering for model validation. The output meta-models are useful to facilitate benefit verification of flexible platform decision for light-duty cordless drills.
Key words: META-MODELING, FLEXIBLE PRODUCT PLATFORM, LIGHT-DUTY CORDLESS DRILL, DECISION SUPPORT, OPTIMIZATION MODEL

1. Introduction

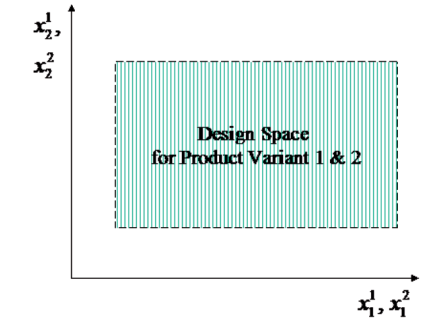
The paradigm of mass customization (MC) has been extensively researched to offer a great promising road for producing products or systems with sufficient variety and economic efficiency [1]. Product platform is one among those excellent methods. Generally, product platform is defined as "the set of common components, modules, or parts from which a stream of derivative products can be efficiently developed and launched" [2]. The major advantage of product platform method is to reduce manufacturing cost or lead time by using common assets across a company's product series [3][4]. Such common assets could be manufacturing processes, product techniques, legacy, and intellectual property, etc [5]. Particularly, it is not rare to treat platform as common building blocks or components in different product variants among a product family. In this sense, optimal design of a product platform could be reduced to the decision of platform commonality, so that overall manufacturing cost or lead time can be minimized.

Platform commonality decides the sharing relationship of components or features among product variants thus the saving of variety costs due to such sharing [6]. The design of product variants with commonality needs to set the interrelationship before searching solutions for each of them in the *design space*. In the simple scenario shown in Figure 1a, the design space is defined by two independent design variables x_1, x_2 and their lower & upper boundaries, and $f_1(x_1, x_2)$ and $f_2(x_1, x_2)$ are both *the-less-the-better* performance metrics. When the platform-based product variants are designed, separate targets f_1^1 and f_1^2 of $f_1(x_1, x_2)$ are set as shown in Figure 1b. If each variant is individually designed, the solution configuration of (x_1^1, x_2^1) for product variant 1 and (x_1^2, x_2^2) for product variant 2 can be found at the points P^1 and P^2 on the pareto frontier, respectively. Since x_1 is hosted on component A and x_2 is hosted on component B. If component A is shared, it constraints the final configuration solutions with $x_1^1 = x_1^2$. It is most likely that the non-dominant points of P^1 and P^2 can not meet the constraints. Thus, the state of at least one product variant off the pareto frontier has to be accepted, which means a performance loss along the axis of $f_2(x_1, x_2)$ to gain cost saving. Therefore, the decision of platform commonality is essentially an optimization problem which trades off gain on cost saving with, at least, loss on technical performance.

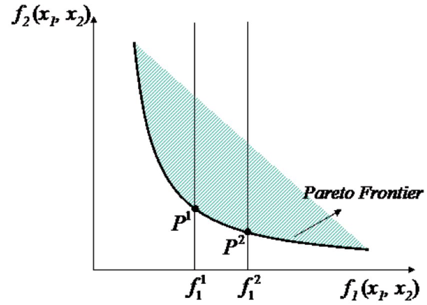
In this paper, based on the multi-objective optimization model of platform commonality decision proposed by the first author in his previous research [7], a set of technical model and cost model of cordless drill is developed to complete the case research of optimal settings of platform-based variants of light-duty cordless drills. The paper is organized as follows. In the next section, the optimization model of platform commonality is recalled, and application details of cordless drills are discussed. In Section 3, the functions of performance metrics for cordless drills are separately formulated based on related domain theories or field knowledge, and cost model is analyzed in details. The case product of light-duty cordless drill is analyzed through reverse engineering to validate the developed models. Section 4 shows an exemplified computation case under uniform demand condition. Finally, conclusions and future research are made in Section 5.

2. An optimization model of flexible platform commonality for light-duty cordless drill

Cordless drill is a mature commercial product in the power tool consumer market. After many years of power tools development in a one-at-a-time mode, Black & Decker redesigned its power tool line using the platform-based strategy for cost reduction. Standardization of subsystems and components sharing are employed to lower its tooling cost. Continuous renewal of partial subsystems, *e.g.* Black & Decker's proprietary motor design, has been practiced to leverage commonality from a previous platform to a new one. Cordless drills can be considered as one of the market segments for general power tools. Their vertical segmentation could be made depending on the applied battery voltage of drills, as shown in figure 2, it could be categorized as light-duty niche (below 9.6V), home-duty niche (9.6V~12V), and heavy-duty niche (14.4V~18V).



a) design space



b) pareto frontier

Figure 1. Performance loss for platform-based variants design

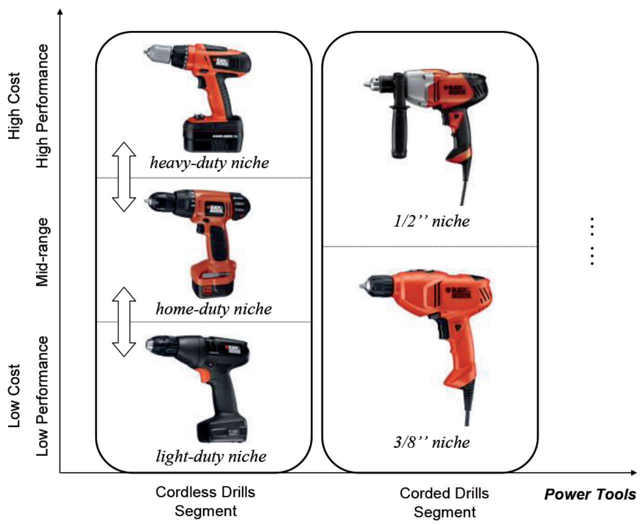


Figure 2. Market segmentation of power drills

In the light-duty niche, the platform-based drill variants are normally differentiated by the sole performance attribute of *rated output torque* at a given rated speed. For the following analyzed case in this research, four predefined drill variants of light-duty cordless drills are set, respectively, 4Nm, 6Nm, 8Nm, 10Nm as their customization targets of rated output torque. Then, the optimal design of the platform-based cordless drills can be reduced to the following configuration settings.

2.1. Optimization objective

Total production cost (TPC) is decided as the global objective to be minimized. Magnan et al identified that companies always give the highest preference to the cost-based strategy where production cost takes a major place [8]. In this model, TPC takes the following general expression:

$$\mathrm{TPC} = \sum_{\text{component variations}} \text{Fixed Cost} \times \text{Number of Component Variations} + \sum_{\text{product variants}} \text{Variable Cost} \times \text{Product Demand} \quad (1)$$

2.2. Decision variables

If each drill variant is individually designed, the decision variables are just the design variables of cordless drill; the optimization for each variant becomes searching the best configuration values of the selected design variables in order to get the solution with minimal TPC. However, when multiple platform-based variants are optimized together, additional decision variables are necessary to represent the sharing relationship of components between drill variants. Any commonization pattern of a component is denoted as one partition mode (p-mode), and each platform component is allowed being shared among drill variants in a flexible manner, that is, a platform component could be shared by any number of variants, if necessary. Thus, p-mode for each component should be treated as additional decision variables in the optimization model of platform-based drill variants design. Such a model construct actually means the flexible platform commonality.

2.3. The optimization model of platform-based cordless drills with flexible commonality

Optimization model of platform-based cordless drills with flexible commonality involves two decision layers: the layer of commonization patterns, *i.e.* p-mode, for the involved components, and the layer of design configurations for drill variants. Therefore, the platform optimization with flexible commonality could be modelled as the following,

$$\begin{cases} Minimize \\ TPC = \sum_{k=1}^{n} \{ \sum_{j=1}^{p} D(j) \cdot VC_k (C_k \mid x_i^j) + N(L_k) \cdot FC_k \} \\ s.t.\, T^j (x_1^j, ..., x_m^j) \ge T(j); \\ \quad L_k \in \{p - mode\}; \\ \quad x_i^j \in [x_i^{lower}, x_i^{upper}]; \\ \quad i = 1,...,m;\ j = 1,..., p;\ k = 1,...,n. \end{cases} \quad (2)$$

Where TPC represents the *total production cost* of the entire light-duty cordless drill family with p variants, n components and m key design variables; j, k, i denote the indices of, respectively, product variants, components, and design variables; $T^j (x_1^j,...,x_m^j)$ is the function of the customer metrics for the jth product variant and $T(j)$ is its target; $D(j)$ is the forecasting demand for the jth product variant and for its kth component as well; VC_k is the variable cost for the kth component of the jth product variant, and is represented as function of the subgroup of the design variables x_i^j that are hosted to the kth component C_k; FC_k is the fixed/changeover cost to producing one variant for the kth component; L_k is the variable partition mode for the kth component; it constrains the valuing pattern of design variables associated with the kth component; $N(L_k)$ calculates the partition number of L_k, which decides the number of variants for the k th component.; and x_i^{lower}, x_i^{upper} are the lower and upper bounds of the ith design variable.

3. Meta-modelling for light-duty cordless drill

To complete the optimization model of flexible platform-based cordless drill design, meta-models of rated output torque and total production cost need to be developed by relating them to decision variables. The baseline of light-duty cordless drills in this research is decomposed into *m=6* key design variables which are hosted into *n=3* components. The three components are, respectively, motor, battery, and speed changer; and the six selected key design variables are, respectively, supply voltage as $U(x_1)$, armature length as $L(x_2)$, total turns of armature winding as $N_N(x_3)$, permanent magnet thickness as $t_{PM}(x_4)$, and speed reduction ratio $mn(x_5, x_6)$.

3.1. The meta-model of rated output torque

The motor of the investigated cordless drills is the type of permanent magnet excited DC motor. The main advantages of a permanent magnet excited DC motor are the high power efficiency and the comparatively low costs of the DC/DC converter needed for speed control. The speed can be simply controlled by adjusting the armature voltage due to its linear characteristic curve (Fig. 3). The torque is proportional to the armature current, which can be easily measured. The fundamental equation of the developed torque on a DC motor is $T_d = K \cdot \varphi \cdot I$ [9], where K is the machine constant (or torque constant), φ is the magnetic flux that functions on the armature windings, and I is the current in the armature circuit. In this research, a 6-pole permanent magnet stator construction and triple-T armature winding on the rotor is fixed for all the drill variants. Comparing with 2-pole or 4-pole construction, 6-pole construction allows a smaller motor size and weight at the same level of power and efficiency. Meanwhile, triple-T winding construction "represents a cost-effective (manufacturing) solution for low power products" [10]. The machines constant K has the following expression: $K = \frac{p}{2\pi a} N_N$, where p is the number of pole pairs and a is the number of pairs of armature current parallel paths. It is supposed that three parallel current paths for the current I are employed (triple-T winding), and three pairs of poles, *i.e.* six poles in all, are set for the permanent magnet on the stator. Thus, the expression for the investigated case should be $K = \frac{1}{2\pi} N_N$.

It is supposed that there is no flux leakage and the length of the air gap is fixed at its minimum feasible value. Therefore, there is $A_{gap} B_{gap} = A_{PM} B_{PM} / \mu_{ra}$ at air-gap, where μ_{ra} is the relative permeability of permanent magnet. With $A_{PM} = L \cdot t_{PM}$, it can get $\varphi = L \cdot t_{PM} \cdot B_{PM} / \mu_{ra}$, and its average value remains constant if the permanent magnet material has been fixed and the armature reaction from *MMF* is neglected. Further, the flux density at the air gap can be computed through $B_{gap} = A_{PM} B_{PM} / A_{gap} \mu_{ra} = t_{PM} B_{PM} / t_{arc} \mu_{ra}$, where t_{arc} is the effective air-gap thickness (the arc between two PM pieces). In this research, the magnet flux density that functions on the armature winding is determined only by the armature length L and the thickness of the PM segment t_{PM}. The total magnetic flux of the performance magnets is approximated as $\varphi = B_{gap} \cdot L \cdot 2r_{wire} \cdot N_N$. The back EMF can be derived as $E = K \cdot \varphi \cdot \omega$ (rated rotary speed ω is known), while the those circuit indicates the relationship of $U = E + I \cdot R_a$ where R_a is the equivalent electric resistance and $R_a = R_0 + \frac{\rho(2L + 2l_{span})}{A_{wire}} N_N$. For triple-T armature winding, $l_{span} = \frac{2\pi \cdot r_a}{3}$ where r_a is the armature radius and $r_a = r_0 - t_{PM} - t_{gap}$. Combining the formula mentioned above, the developed torque on the component motor could be explicitly expressed as the function of the chosen design variables. Motor power efficiency should be high enough in order to avoid heavy power loss. Motor efficiency is given by $\eta = P_{out} / P_{in} = T_d \omega / UI$.

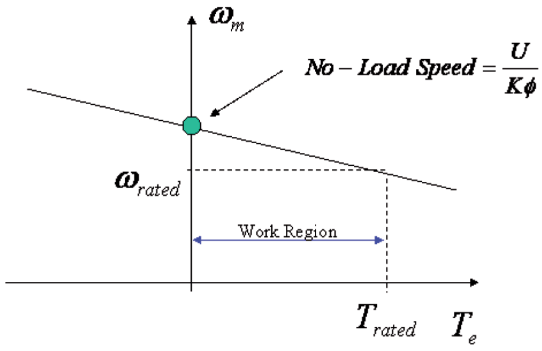


Figure 3. Characteristic curve of a permanent magnet dc motor

Since batteries package only functions as a supply resource of voltage and current, the above equation has already included the voltage $\boldsymbol{U}$ of the battery if no voltage drop through contact and wire is assumed. The batteries materials used in the referred cordless drill are Nickel-metal-hydride (NiMH) with cell voltage 1.2V, by which step the supplied voltage can be changed. That is, the supplied voltage can only be 1.2V, 2.4V, 3.6V, 4.8V … *etc* by adding up the battery cell number.

The speed changer (also gear reducer, speed reducer, or gearbox) consists of a set of gears that convert input motion into output motion with lower rotary speed and higher torque. In the investigated cordless drills, a speed changer with a single reduction ratio is employed. It can be seen that the speed changer has two-stage gears thus it provides a dual speed reduction. Therefore, its speed reduction ratio has the format of $(m:1) \times (n:1)$, where m and n both are integers determined by the number of teeth the two gears. It is supposed that 1) there is no energy loss at the speed reduction, 2) two-stage gear reduction is fixed, and 3) the diametral pitches of the two large gears are fixed at 48 and 32, and their thicknesses at 5mm and 6mm, and pressure angles at 20° (standard) and 14.5° (traditional), respectively, 4) only the teeth numbers are variable, so that the diameter of the gear will be affected. The speed reduction function of the speed changer simply follows $\omega_m T_e = \omega_{out} T_{out}$, thus the speed reduction ratio is defined as $mn = \omega_m / \omega_{out} = T_{out} / T_e$.

It is noted that, to facilitate the modelling process, the following parameters are frozen with given values based on field knowledge:

– Triple-T armature winding,
– 6-pole permanent magnet construction,
– D_{wire} – Diameter of winding wire,
– p – Number of pole pairs (=3),
– a – Number of pairs of armature current parallel paths (=3),
– r_{wire} – Radius of winding wire,
– ω – Rotary speed on rotor,
– μ_{ra} – Relative permeability of permanent magnet,
– r_0 – Outer radius,
– t_{gap} – Air-gap length,

– ρ – Resistivity of copper,
– r_a – Armature radius (m),
– R_0 – Additional resistance (ohm).

1.2. The meta-model of total production cost

Intuitionally, variable cost function of each component can be separately built up by relating to its corresponding design variables, and the overall variable cost for the whole product can be obtained by merging the following component-level VC functions:

– Battery cost:

$$c_{battery} = \rho_{battery}(U/1.2V),$$

where $\rho_{battery}$ is the cost per unit battery cell;

– Magnet cost:

$$c_{magnet} = \rho_{magnet} t_{arc} t_{PM} L,$$

where ρ_{magnet} is the cost per unit volume permanent magnet (m^3);

– Copper wire cost:

$$c_{copper} = \rho_{copper} N_N (2L + 2l_{span}) A_{wire},$$

where ρ_{copper} is the cost per unit volume copper (m^3);

– Armature cost:

$$c_{armature} = \rho_{armature} L \pi r_a^2,$$

where $\rho_{armature}$ is the cost per unit volume armature;

– Speed changer cost:

$$c_{sc} = c_0 + \rho_{steel} \cdot [0.005\pi \cdot (0.0254 \cdot \frac{Teeth_m + 2}{48 \cdot 2})^2 + $$
$$+0.006\pi \cdot (0.0254 \cdot \frac{Teetch_n + 2}{32 \cdot 2})^2],$$

where ρ_{steel} is the cost per unit volume steel (m^3).

The fixed costs of the investigated components, *i.e.* battery, motor, speed changer, and casing can be separated into family-level and variant-level fixed costs. The variant-level fixed cost can be estimated as (*the fixed acquisition cost of N component variants - the fixed acquisition cost of N-1 component variants*). The family-level fixed cost can be estimated as (*the fixed acquisition cost of only one component variant – the variant-level fixed cost*). Actually, the total fixed cost of the drill family is varied by the commonalities of the components that are represented as the decision variables of *P-mode* in the integrated optimization model.

4. Application and computation

Finally, as a computation application for the optimization model of platform decision problem expressed by equation (2), an exemplified research case problem of a platform-based drill family with four drill variants targeting demanded set of rated output torques is applied and solved with a specific simulated annealing algorithm for demonstration of the meta-modeling effectiveness. The iteration history of seeking solution with the SA algorithm under the assumed condition of uniform demand for all the drill variants can be seen in figure 4.

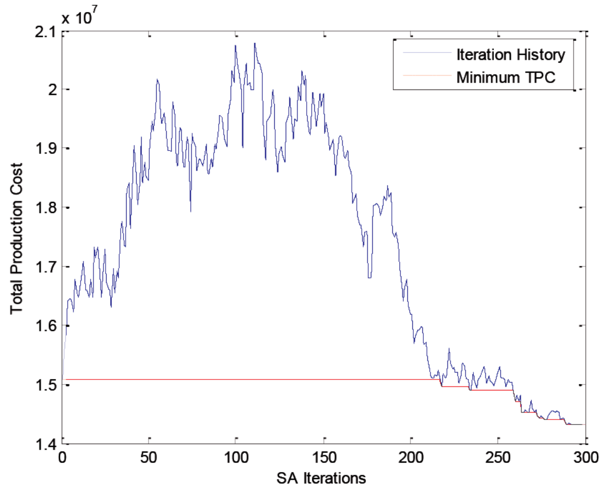


Figure 4. Iteration history with simulated annealing algorithm for the drill platform

5. Conclusions

Flexible platform strategy offers manufacturers a competitive advantage by introducing solid trade-off balance between cost saving and performance loss. To quantitatively analyze the effect of such balance in certain case products, their meta-modeling needs to be well developed. In this research, an optimization model of flexible platform design is presented, and the meta-modeling of light-duty cordless drill as a case product is developed in details. The relationship models of rated output torque and total production cost as function of selected key design variables and key components to the drill platform are established to facilitate future simulation work. With these, the whole set of flexible platform meta-modelling is fully prepared for quantitative simulation to disclose the underlying platform trade-off of light-duty cordless drills family. Therefore, an immediate next-step research work is to employ the output models in this paper to make simulations and verify the benefits of flexible platform for the product family of light-duty cordless drills.

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The creative design of special rewinding machine based on KANO/QFD and TRIZ

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Abstract
Non-standard equipment design needs the support of creative design strategy, our main task is to design a special rewinding machine. To comprehensively analyze customer requirements and creatively solve technical problem, an integrated innovation design model based on KANO, QFD and TRIZ theory is proposed. The innovation de-