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A Research on Model of Flexible Module in Product Family Based on SML

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Abstract: To support product family design for mass customization, sach-merkleisten was introduced into flexible module modeling which is one of product family design's important content. And correlation analysis was used to validate and weight relationship in main parameters. After validated the parameters' relationship, regression analysis was used to find the regression function so that the module can be expanded. An example was given to show the method's practicability.

Keywords: Flexible module; correlation analysis; regression analysis; modeling; SML.

1. Introduction

The goal of MC (Mass Customization) is to provide the fast and characteristic product for the customer with the efficiency and cost of the large-scale production mode, which can produce standard workpieces that meet customer's needs, and assemble and reform the product according to the customers' characteristic needs. It is one of the main modes of manufacturing industry development in information age, which gets the goal of combining MP (Mass Production) with the customers' characteristic.

Product family design (PFD) is a key technique for mass customization. Flexible module is one of PFD's important content, many scholars has studied on it's concept and programming technique. Dr. Huang Hua used Analytic hierarchy process (AHP) to weight the different influence factors and the interaction among the parts and the related matrix were obtained. He used the fuzzy clustering method to operate the matrix for a flexible modular division [1]. Dr. Gao Shuying presented the function model of mechanical products generalized modular design system, the flexible module data model is one of the main data models of the system. She analyzed the types of information of flexible module data model, and studied the design knowledge of flexible module and its computer expression [2]. Dr. Wang Aimin constructed the quantified Design Structure Matrix (DSM) based on the functional and structural interface relations analysis, achieved components' clustering by utilizing product family design sequence. And then the product platform is realized based on the modularized product family by synthetically considering above tow layers' interface relations[3]. Prof. Lu Yunjun presented a method of product configuration knowledge expression based on ontology and tabular layouts of article characteristics to realize rapid design of product family [4].

In this paper, based on previous studies, we utilize SML to establish model of flexible module, find out intrinsic relationship among the main parameters by correlation analysis and regression analysis. Thus it is easy to expand the module to facilitate meeting customer individual needs, suitable for modeling flexible module in mass production mode.

2. The function structure model of flexible module based on SML

2.1. *The concepts*

SML, that is tabular layouts of article characteristics(TLAC), is a list that combine and arrange the related object features(style feature, function feature, geometrical feature, material feature, color feature, technical feature and so on). SML technology originates in Germany at the beginning of 70's. German established the nation information flow standard by SML technology, and started to establish SML series standard since 1985. SML technique is used to constitute product configuration model.

Flexible Module is a set of parameterized model character module structure by modular division of product structure. It is some carriers that take on particular function and structure. Its interface and structure have parameterized characteristic. If all joints were given according to design, that is, it create a idiographic component. The component is a instance of flexible module.

2.2. *The steps establishing the flexible module based on SML*

Step1 Module function analysis

Modular structure with the function is found by analyzing modular function. It is ready for identifying characteristics in SML.

Step2 Module topological structure analysis

Module topological structure is analyzed to reduce the module category and quantity, decrease the production cost and enhance the product quality.

Step3 Module configuration analysis

A module can be made of many parts. There are two constrains in the modular and its parts' SML.

Under constrain: Module characteristics constrains the parts ones, however the constrained characteristics cannot determine the only part but a set of parts. In this situation, the choice needs to be made by the designer.

Complete constrain: Module characteristics constrain the parts ones uniquely. If all the constraints of the module are complete constrain, the module can be automatically designed from top to down. And the designer can get the structure and joint of the module, which is ready for SML.

Step4 Module parameter analysis

Analyzing module parameter is to reduce and unify the module parameters. There are many types of modular parameter, including the following three ones.

Independent characteristic: The characteristic only show the range, which is not restricted to other ones. When a new instance is derived from the module, the characteristic value needs be input.

Functional characteristic: The characteristic value depends on the other ones completely, which is expressed by the formula. When a new instance is derived from the module, the characteristic value can be get from the formula.

Conditional characteristic: The module characteristic value range is constrained by the other and deprived ones. When a new instance is derived from a module, the characteristic also needs be input manually.

When confirming the module SML, the parameters are classified according to the above three categories in order to get good management. For variant design, the number of features can be differently combined to determine an instance.

Step5 the module SML establishment

The SML can be established after the above analysis. The corresponding codes can be used to express the main parameters of the module. There are the main following principles.

(1) The characteristics in the table can describe the module fully and clearly.

(2) Module parameters should be as concise as possible, only including the variant parameters in variant design.

(3) If the module is composed of the only part, the characteristics should focus on the dimension, accuracy, materials and so on; and if the module is composed of multiple components, the choice should focus on the assembly precision, assembly dimensions and so on .

3. *The main parameters analysis*

In the development of the enterprise, a variety of design experience and data are got together, forming a series of module family. The main parameters of the module family are expanded to meet market's demand by the analysis of these

3.1. *Correlation analysis*

Correlation analysis is a mathematical method based on processing the variable relationship, which has been successfully applied to quality control, weather and earthquake forecasting and so on. It is used to quantitatively describe the relevant direction and grade between the two variables x and y. when the correlation coefficient r>0, the two variables are positive correlation; r<0, the negative correlation. Normally, when |r|<0.3, the relationship of x and y is called a weak correlation; when 0.3≤|r|<0.5, it is low correlation; when 0.5≤|r|<0.8, it is significant correlation; when |r|≥0.8, it is highly significant correlation. Because of the distribution of each parameter is not very clear, simple correlation analysis firstly should be carried on. The formula is as following:

$$r_{xy} = 1 - \frac{6\sum_{i=1}^{n} d^2}{n(n^2-1)} \tag{1}$$

Where rxy is the correlation coefficient, d is the level difference between each pair of data, n is the total number of the two columns. After simple analysis is completed, the correlation coefficient must be checked by the formula (2):

$$t = \frac{r_{xy}}{\sqrt{\frac{1-r_{xy}^2}{n-2}}} \tag{2}$$

Where n-2 is freedom degree, calculating the probability when correlation coefficient is 0.

As simple correlation analysis does not consider the third variable effecting the correlation of the other two variables, leading to the "false correlation" or "implied correlation" phenomenon [5]. In order to get rid of the above problem, the partial correlation analysis need be carried on based on the simple correlation analysis, so as to get the real correlation of the two variables. Supposed there are three variables x, y, z, the partial correlation coefficient between x and y is as following:

$$r_{xy,z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{(1-r_{xz}^2)(1-r_{yz}^2)}} \tag{3}$$

Where rxz, ryz and rxy is the simple correlation coefficient of two variables. The significant testing of partial correlation coefficient also uses two-tailed t-test hypothesis. Hypothesis testing formula is:

$$t=\frac{r\sqrt{n-k-2}}{\sqrt{1-r^2}} \quad (4)$$

Where r is the partial correlation coefficient, n is the number of samples; k is the number of control variables, (n-k-2) is the degrees of freedom.

3.2. *Regression analysis*

Regression analysis is a statistical method that studies the non-deterministic relationship among variables. In this paper, the regression analysis is used to measure quantity changes of the two or more correlation variables, according to some mathematical equation (model), so as to estimate or predicted the dependent variables based on the independent variables. Least-squares method (LS) is one of the most commonly regression analysis methods.

f (x) is a function defined on the interval [a, b], $\{x_i\}_{i=0}^{n}$ is n+1 different points in the interval, Φ is a function class. So the least squares problem is to find the function g(x) in Φ so that the distance between f(x) and g(x) is minimum, and it takes norm-2. Namely, find a function $g(x)\in\Phi$ to set $R_2=\sqrt{\sum_{i=0}^{n}\left(g(x_i)-f(x_i)\right)^2}$ to minimum, if

$\Phi=span\{\varphi_0,\varphi_1,\cdots\varphi_n\}$,

$g(x)=a_0\varphi_0(x)+\cdots+a_n\varphi_n(x)$, then

$\left\|g(x)-f(x)\right\|_D=\min_{\varphi\in\Phi}\left\|\varphi(x)-f(x)\right\|_D$, namely

$\left\|f(x)-\left(a_0\varphi_0(x)+\cdots+a_n\varphi_n(x)\right)\right\|_D$ is minimum about the coefficient $\{a_0,a_1,\cdots a_n\}$,

$$\begin{aligned}&\left\|f(x)-\left(a_0\varphi_0(x)+\cdots+a_n\varphi_n(x)\right)\right\|_D^2\\&=\|f\|_D^2-2(f,a_0\varphi_0(x)+\cdots+a_n\varphi_n(x))_D+\left\|a_0\varphi_0(x)+\cdots+a_n\varphi_n(x)\right\|_D^2\\&=\|f\|_D^2-2\sum_{k=0}^{n}a_k\left(f,\varphi_k\right)+\sum_{i,k=0}^{n}a_ia_k\left(\varphi_i,\varphi_k\right)\\&=Q(a_0,a_1,\cdots,a_n)\end{aligned}$$

Because of its minimum on the coefficient, it is:

$$\frac{\partial Q}{\partial a_i}=0, i=0,\cdots,n$$

namely $\sum_{k=0}^{n}a_k(\varphi_i,\varphi_k)=(f,\varphi_i), i=0,\cdots,n$.

Its corresponding matrix is:

$$\begin{pmatrix}(\varphi_0,\varphi_0)_D & \cdots & (\varphi_0,\varphi_n)_D\\ \vdots & \ddots & \vdots\\ (\varphi_n,\varphi_0)_D & \cdots & (\varphi_n,\varphi_n)_D\end{pmatrix}\begin{pmatrix}a_0\\ \vdots\\ a_n\end{pmatrix}=\begin{pmatrix}(f,\varphi_0)_D\\ \vdots\\ (f,\varphi_n)_D\end{pmatrix}$$

Because $\{\varphi_0,\varphi_1,\cdots\varphi_n\}$ is linear independent, the equation has a unique solution.

4. Example

Based on the above given steps of the flexible modules establishment, this paper takes the working equipment of backhoe hydraulic excavator as an example, illuminating the module establishment and parameters analysis.

(1) Function analysis

The backhoe device is a major work unit in hydraulic excavator, which is the core module of the hydraulic excavator.

The device achieves a variety of actions in mining process by changing hydraulic cylinder stroke. Backhoe works as follows: Firstly, adjusting the boom in position for mining, then rotating the arm and bucket, when filling the bucket, enhancing the boom to detach the bucket from the soil, and turning to unloading position at the same time, finally reversing the bucket to unload. And then it returns to starting position for the next operating cycle. Boom hydraulic cylinder is mainly used to adjust the location and is not directly tap the soil; Arm digging can get larger digging trip, but the digging force is smaller. Bucket digging can get shorter trip, but this need a larger force to ensure that mining can dig a large thickness of the soil to fill bucket at the end. So the most digging force is normally provided by adjusting hydraulic cylinder of bucket to achieve. The function modeling is as following:

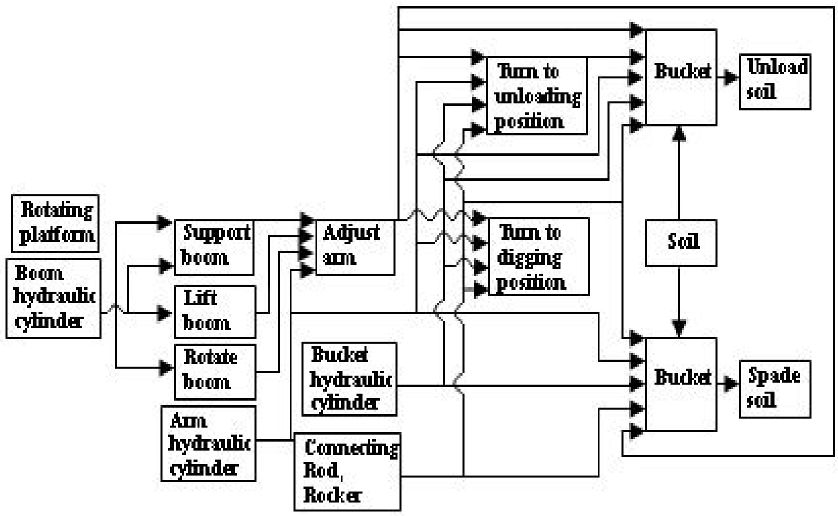


Figure 1. The working equipment of backhoe IDEF0

(2) Module topology analysis

Function: digging pit or drains, mining ore or coal, removeing old buildings, flatting ground, building roads, digging trenches and bunkers, constructing military buildings, etc. In its framework, Hydraulic excavator takes on large digging and traction force, light machinery weight, smooth transmission, high efficiency, compact structure, etc. All the working components have the hinge joints, which is easy for replacement.

(3) Module configuration analysis

The backhoe working device is composed of eight parts by hitched-connection. Thus, we can take the device as the assembly part by the eight components.

Figure 2 shows 3D model in order to clearly understand the assemble relationship between the components.

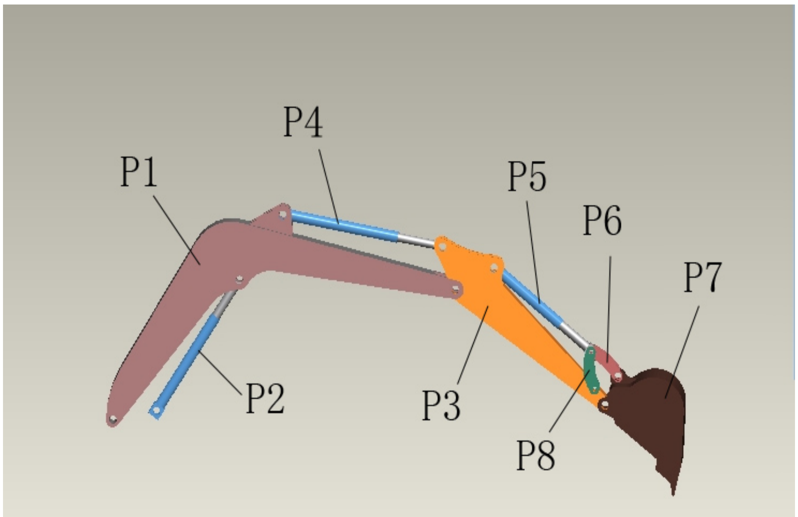


Figure 2. Backhoe working device configuration

In the Figure, P1 is the boom, P2 is the boom cylinder, P3 is the arm, P4 is the arm hydraulic cylinder, P5 is the bucket hydraulic cylinder, P6 is the connecting rod, P7 is the bucket, P8 is the rocker.

(4) Module parameters analysis

For the module consisted of the individual part, its parameters are generally considered about geometry, precision, and materials and other information; and for the assembly module, its parameters is considered about assembly dimensions and co-ordination information between the parts. The module is assembled of eight parts, the main parameters are: bucket capacity, arm length, boom length, maximum transport length, maximum digging reach, maximum digging depth, maximum cutting height, maximum dumping height, minimum swing radius, maximum vertical wall, arm crowd force, bucket digging force. Bucket capacity is determined by the basic requirements such as the given working conditions, productivity in design task book, and other parameters are based on bucket capacity. So, the parameter bucket capacity takes on independent feature, which is one of the classification hallmarks of hydraulic excavator. Other parameters can be deduced from engineering experience and 3D model.

(5) SML establishment

Based on the above analysis, the SML is established as following:

1tol	SML GB/T 10091 XX–XX												
	Working device of backhoe												
Characteristic code	A	A1	B1	B2	B3	C	…	J3	K1	K2	L	M
Characteristic name	Bucket Capacity	Bucket Width	Boom	Arm	Bucket	Maximum transport Length	…	Hydraulic Cylinder of bucket	Arm Crowd Force	Bucket Digging Force	Connecting Rod	Rocker
unit	m^3	mm	—	—	—	mm	…	—	kN	kN	—	—
01	0.016	230	01-01	01-02	01-03	955	…	01-06	6.1	10.3	01-07	01-08
02	0.018	300	02-01	02-02	02-03	970	…	02-06	5.9	11.	02-07	02-08
03	0.020	250	03-01	03-02	03-03	1220	…	03-06	10.3	16.0	03-07	03-08
…	…	…	…	…	…	…	…	…	…	…	…	…

1tol	SML GB/T 10091 XX–XX					
	Boom					
Characteristic code	A1	A2	B	C	D	…
Characteristic name	Length	Height	Aperture	Material	Weight	…
unit	m	mm	mm	—	kg	…
01-01	1.35	580	38	Q235	2670	…
02-01	1.46	650	40	Q235	2800	…
03-01	1.82	880	46	Q235	3590	…
…	…	…	…	…	…	…

…

1tol	SML GB/T 10091 XX–XX						
	Bucket						
Characteristic code	A1	A2	B	C	D1	D2	…
Characteristic name	Cutting Radius	Height	Aperture	Material	Side Angle	Tine Angle	…
unit	mm	mm	mm	—	—	—	…
01-03	245	298	36	Q345B	30	20	…
02-03	360	427	40	Q345B	30	21	…
03-03	245	300	42	Q345B	35	20	…
…	…	…	…	…	…		…

…

Figure 3. Backhoe working device SML

(6) Regression model

Through the collection of the main parameters, the base parameter library of the working device is shown in Table 1.

Table 1 the base parameter library of the working device

Bucket Capacity	Bucket Width	Arm Length	Boom Length	Maximum transport Length	Maximum Digging Reach	Maximum Digging Depth	Maximum Cutting Height	Maximum Dumping Height	Minimum Swing Radius	Maximum Vertical Wall	Arm Crowd Force	Bucket Digging Force
0.016	230	0.70	1.35	955	2,830	1,600	2,840	2,050	1,100	1,450	6.1	10.3
0.018	300	0.81	1.46	970	3,220	1,780	3,010	2,220	1,310	1,670	5.9	11.7
0.018	300	0.81	1.46	970	3,220	1,780	3,010	2,220	1,310	1,670	5.9	117.0
0.020	250	0.93	1.82	1,220	3,900	2,170	3,560	2,530	1,610	1,830	10.3	16.0
0.040	250	1.00	1.88		4,300	2,320	4,140	2,870	1,880	1,930	12.0	18.6
0.110	550	1.32	2.47		5,220	3,060	4,720	3,330	2,230	2,670	19.1	27.5
0.130	360	1.62	3.72	2,550	6,320	4,170	7,150	5,060	1,720	3,730	38.0	55.0
0.190	450	2.10	4.60	2,580	7,900	5,150	8,370	5,960	2,310	4,650	73.0	99.0
0.910		2.91	5.68	2,970	9,910	6,660	9,610	6,790	3,540	6,040	109.0	151.0
1.000	1,130	2.96	6.00	3,070	10,290	6,960	10,160	7,200	3,440	6,030	125.0	180.0
1.200		2.96	6.00	3,100	10,270	6,950	9,630	6,760	3,870	6,020	125.0	180.0
1.300		2.96	6.00	3,100	10,270	6,950	9,630	6,760	3,870	6,020	125.0	180.0
1.380		3.20	6.40	3,230	11,100	7,360	10,250	7,150	4,490	6,460	172.0	237.0
1.400	1,280	3.20	6.40	3,270	11,100	7,380	10,360	7,240	4,460	6,420	176.0	234.0
1.900	1,540	3.40	7.00	3,450	12,050	7,890	10,950	7,540	4,840	6,780	202.0	269.0
2.100	1,560	3.40	7.00	3,480	12,060	7,770	11,060	7,650	4,840	7,100	218.0	288.0
3.500	1,870	3.70	8.40	4,570	14,100	8,870	13,000	9,080	5,950	6,840	324.0	402.0

(a) The simple correlation analysis of the main parameters

Based on the analysis of the base parameter library in statistical software SPSS 13.0 for Windows, we got the SPEARMAM simple correlation about the main parameters, as shown in Table 2.

(b) The main parameters partial correlation analysis

According to the above the simple correlation analysis, it may be two exceptions: one is that the SPEARMAN correlation coefficient is great, but curve fitting is poorly; the other is that the SPEARMAN correlation coefficient is small, but curve fitting is very well. The two cases correspond to above "false correlation" and "implied correlation". Therefore the main parameters need to carry on partial correlation analysis, which is shown in Table 3.

Table 2 main parameters correlation coefficient

		Bucket Capacity	Bucket Width	Arm Length	…	Minimum Swing Radius	Maximum Vertical Wall	Arm Crowd Force	Bucket Digging Force
Bucket Capacity	Correlation Coefficient	1.000	0.938**	0.996**	…	0.986**	0.972**	0.990**	0.951**
	Sig. (2-tailed)	.	0.000	0.000	…	0.000	0.000	0.000	0.000
	N	17	13	17	…	17	17	17	17
Bucket Width	Correlation Coefficient	0.938**	1.000	0.936**	…	0.928**	0.932**	0.899**	0.917**
	Sig. (2-tailed)	0.000	.	0.000	…	0.000	0.000	0.000	0.000
	N	13	13	13	…	13	13	13	13
…	…	…	…	…	…	…	…	…	…
Maximum Vertical Wall	Correlation Coefficient	0.972**	0.932**	0.978**	…	0.969**	1.000	0.971**	0.937**
	Sig. (2-tailed)	0.000	0.000	0.000	…	0.000	.	0.000	0.000
	N	17	13	17	…	17	17	17	17
Arm Crowd Force	Correlation Coefficient	0.990**	0.899**	0.991**	…	0.975**	0.971**	1.000	0.934**
	Sig. (2-tailed)	0.000	0.000	0.000	…	0.000	0.000	.	0.000
	N	17	13	17	…	17	17	17	17
Bucket Digging Force	Correlation Coefficient	0.951**	0.917**	0.955**	…	0.942**	0.937**	0.934**	1.000
	Sig. (2-tailed)	0.000	0.000	0.000	…	0.000	0.000	0.000	.
	N	17	13	17	…	17	17	17	17

** Correlation is significant at the 0.01 level (2-tailed)

Table 3 main parameters partial correlation coefficient

Bucket Capacity		Control Variables									
		Bucket Width	Arm Length	Boom Length	…	Maximum Cutting Height	Maximum Dumping Height	Minimum Swing Radius	Maximum Vertical Wall	Arm Crowd Force	Bucket Digging Force
Bucket Width	0.938**		0.832**	0.762**	…	0.831**	0.837**	0.296**	0.892**	-0.007	0.438
Arm Length	0.996**	-0.404		-0.362	…	0.239	0.299	-0.507*	0.837**	-0.545*	-0.010
Boom Length	0.996**	-0.103	0.533*		…	0.773**	0.786**	-0.216	0.856**	-0.566*	0.086
Maximum transport length	0.999**	0.074	0.388	0.080	…	0.553*	0.612**	-0.092	0.626*	-0.478	0.191
Maximum Digging Reach	0.991**	-0.156	0.722**	0.271	…	0.710**	0.718**	-0.326	0.891**	-0.552*	0.113
…	…	…	…	…	…	…	…	…	…	…	…
Minimum Swing Radius	0.986**	0.225	0.837**	0.731**	…	0.805**	0.811**		0.885**	-0.153	0.429
Maximum Vertical Wall	0.972**	-0.477	-0.779**	-0.757**	…	-0.283	-0.200	-0.538*		-0.609*	-0.181
Arm Crowd Force	0.990**	0.792**	0.950**	0.941**	…	0.959**	0.960**	0.813**	0.966**		0.748**
Bucket Digging Force	0.951**	0.571	0.827**	0.788**	…	0.838**	0.844**	0.600**	0.874**	0.051	

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

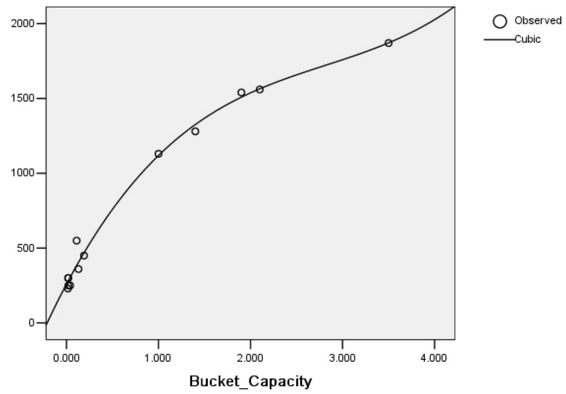
As can be seen from the table, bucket width and arm crowd force have control relationship with each other, but the partial correlation coefficient is very low, both have false correlation; bucket width and bucket digging force have control relationship with each other, large change in the correlation coefficient show both have implied correlation; arm length and bucket width, boom Length, maximum digging reach, maximum cutting height, maximum dumping height, minimum swing radius, arm crowd force control each other, they have implied correlation; between arm length and maximum transport length, maximum digging depth, bucket digging force, partial correlation coefficient is very low, they have false correlation, and so on.

(c) Regression model establishment and test

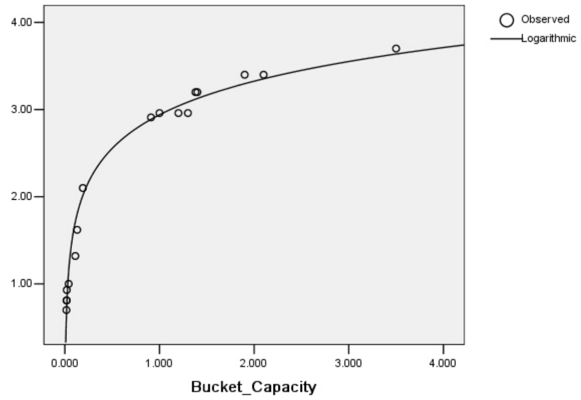
According to the above simple correlation and partial correlation analysis, we take bucket capacity (x) as independent variable, separately take bucket width (y1), arm length (y2), boom length (y3), maximum transport length(y4), maximum digging reach(y5), maximum digging depth(y6), maximum cutting height (y7), minimum dumpping height(y8), minimum swing radius(y9), maximum vertical wall(y10), arm crowd force(y11), bucket digging force (y12) as the dependent variable. Firstly we use 11 regression models to fit each group of variables for regression analysis in SPSS, then select the best model as the regression equation by comparing the coefficient of determination and significance test results [6], which is shown in Table 4. Figure 4 shows four of the corresponding scatter plot and fitting figures.

Table 4 main parameters regression model

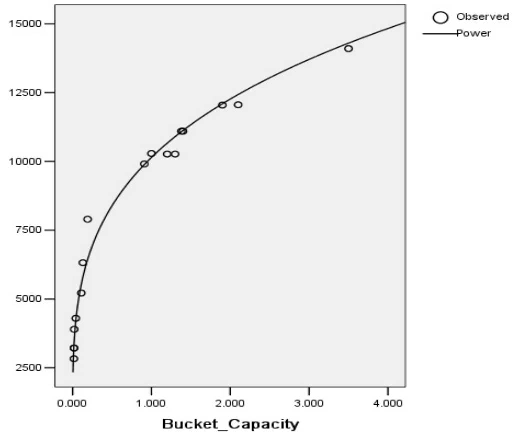
Parameter	Regression function	R Square	F	Sig.	df
Bucket Width	$y1=1259.451+1160.675x-342.019x^2+40.570x^3$	0.991	322.833	0.000	12
Arm Length	$y2=2.940+0.557\ln x$	0.984	897.888	0.000	16
Boom Length	$y3=1.827+7.016x-3.392x^2+0.551x^3$	0.945	75.093	0.000	16
Maximum transport length	$y4=1278.882+3374.889x-1832.560x^2+325.674x^3$	0.892	30.320	0.000	14
Maximum Digging Reach	$y5=10146.480x^{0.274}$	0.879	714.266	0.000	16
Maximum Digging Depth	$y6=6877.432+1302.954\ln x$	0.984	932.310	0.000	16
Maximum Cutting Height	$y7=9895.803+1705.592\ln x$	0.966	428.512	0.000	16
Maximum Dumping Height	$y8=6740.976x^{0.260}$	0.951	293.266	0.000	16
Minimum Swing Radius	$y9=1467.731+2997.934x-878.119x^2+110.775x^3$	0.975	166.572	0.000	16
Maximum Vertical Wall	$y10=1945.559+6898.210x-3226.29x^2+474.509x^3$	0.939	67.024	0.000	16
Arm Crowd Force	$y11=128.344x^{0.719}$	0.975	592.290	0.000	16
Bucket Digging Force	$y12=33.730+148.973x-12.567x^2$	0.943	144.977	0.000	16



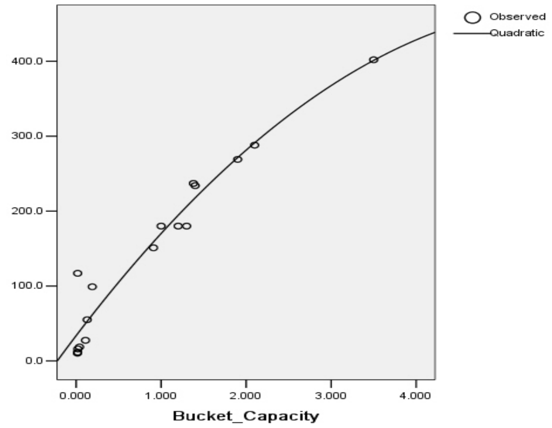
1 .curve fitting between bucket capacity and width



2. curve fitting between bucket capacity and arm length



3. curve fitting between bucket capacity and maximum digging reach



4. curve fitting between bucket capacity and bucket digging force

Figure 4. Four of the corresponding scatter plot and fitting figures

Bucket capacity 0.51 is used to regression model validation: all relatively errors are less than 15%.

5. Conclusions

- By studying the characteristics of flexible module to identify main parameters, shape base parameters library, establish the SML, flexible module can be easily modeled to form a product family to facilitate product series.
- Main parameters correlation analysis can effectively extract and solidify the uncertain interdependence relationship between the main parameters to ensure meaningful regression analysis;
- It is easy to expand flexible modules in family flexible by regression analysis to find out the function relationship between the parameters to establish regression model. Thus we can effectively find and tap the market demand.
- Regression analysis for parameters provides a theoretical basis that help we understand intrinsic relationship in serial products.

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