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Optimizing a Laundering Program for Textiles in a Front-loading Washing Machine and Saving Energy

Wei Bao¹, R. Hugh Gong², Xuemei Ding^{1,3}, Yue Xue¹, Pengfei Li¹, Weichao Fan¹

(1.College of Fashion and Design, Donghua University, Shanghai 200051, China; 2. Textiles, School of Materials, University of Manchester, Manchester, M13 9PL, U.K; 3.Key Laboratory of Clothing Design & Technology, Ministry of Education, Donghua University, Shanghai 200051, China)

Corresponding author:

Xuemei Ding, College of Fashion and Design, Donghua University, Shanghai, China.

Email: fddingxm@dhu.edu.cn

Present address: 1882, West Yan an Road, Shanghai, China

Abstract

The laundering process has significant environmental impact due to the consumption of energy, water and chemicals. This paper optimized an energy-saving laundering program, especially for shirts or other underwear by efficient experiment design to balance the temperature, main wash time and mechanical action. As a result, energy consumption after optimization is around 1/3 lower than the original, and at the same time, detergency and the rate of fabric abrasion are basically the same as the original. What's more, compared with original program, no additional chemicals or water is used. This finding can help the washing machine manufacturers to optimize washing procedures and it will significantly reduce the environmental impact of washing machines.

Key words: Laundering program, Optimization, Energy reduction, Soil removal

1.Introduction

Washing clothes and other home textiles is one of the most widespread housework in the world (Pakula and Stamminger 2010). The laundering process has significant environmental impact due to the consumption of energy, water and chemicals (Figure 1). According to statistics, electricity consumption of washing machines accounts for 6.4 % of total residential electricity in EU-27 (BERTOLDI and ATANASIU 2009). In addition, Life cycle assessment studies on clothes (Chen and He 2014), detergents (Saouter and Van Hoof 2002) and washing machines (Yuan, Zhang et al. 2016) show that the “use” period is usually the most energy-demanding period during these products' life cycle.

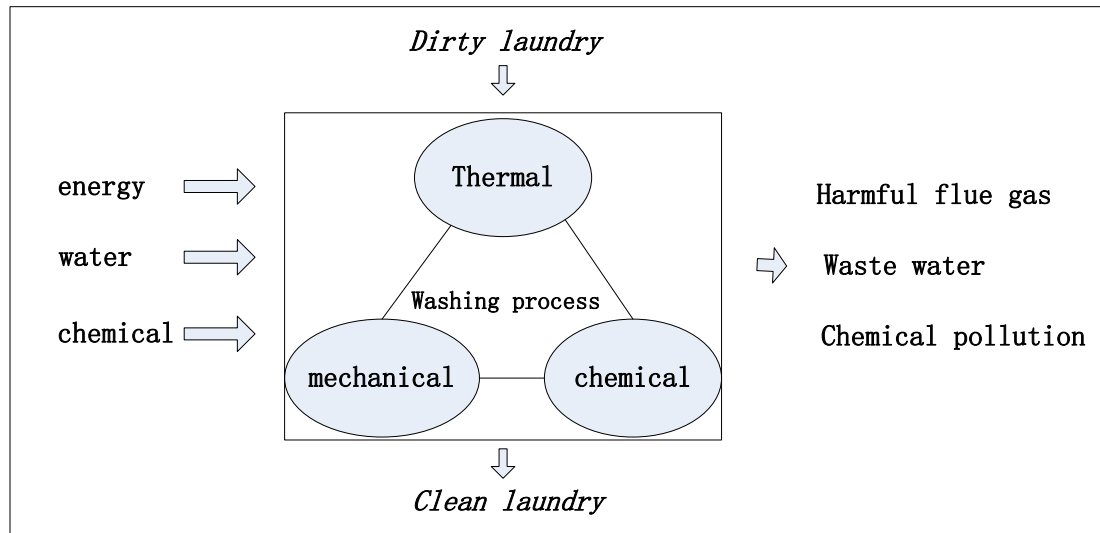


Figure 1 Environmental impact of laundering process

Drum-type washing machines, which are more popular to consumers, use less water than impeller-type ones. However, they are often associated with hot water and longer mechanical agitation, which causes more energy consumption. Experimental tests showed that energy used to heat up the wash load accounts for more than 78% when temperature is above 40 °C (Mozes, Cornelissen et al. 1998) in laundering process. In 2010 the average washing temperature in Germany was 46 °C (Hauthal 2012). Lowering the washing temperature is an effective way to save energy, but it may decrease the clean performance.

According to the Sinner Circle (Figure 2), a laundering procedure is a result of the synergistic actions between temperature, duration, mechanical action and chemical action (Hauthal 2012), so it is important to balance these parameters for sustainable washing procedures without lowering other washing performances, such as cleaning effect and fabric damage. Several studies have investigated the effects of washing conditions on washing performance and the consumption of electricity and water. Lowering the temperature and prolonging the washing time led to a remarkable decrease of the energy consumption while the cleaning performance remained the same (Janczak, Stamminger et al. 2010). However, fabric damage was not considered. In fact, prolonging wash time can easily cause fabric damage, so it is an important performance aspect to consider. Some studies optimized parameters to save energy by increasing detergent or disinfecting agents. Honisch et al. concluded that the loss of

hygiene effectiveness caused by temperature reduction can be compensated by increasing the wash cycle time and/or use of a detergent with activated oxygen bleach (Honisch, Stamminger et al. 2014). Fijan et al. optimized a laundering program to achieve more energy-saving by a transformation from thermal to chemo-thermal action, at the same time ensure disinfection (Fijan, Fijan et al. 2008). Altenbacher et al. implemented an optimal low-temperature laundering procedure, which decreased energy consumption while reaching an adequate disinfection effect with somewhat higher dosages of chemicals and with lower damages to the textiles (Altenbacher, Turk et al. 2011). Although these programs decrease energy consumption, more chemicals were used. Han et al. identified the optimal washing methods in terms of washing efficiency and electricity consumption. To this end, the mechanical action by the washing machine's agitation and the chemical action by detergents were investigated (Han, Chung et al. 2015), but the energy and pollution caused by chemical production were not taken into account.

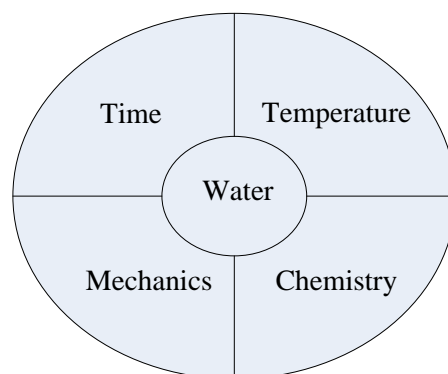


Figure 2 The Sinner Circle (Hauthal 2012)

This research aimed at optimizing a sustainable laundering program which can reduce energy consumption without additional chemicals. The cleaning efficiency and fabric abrasion damage are also considered.

Of the contaminants in the clothes, those from the human body are the most common accounting for up to 70 % of the total. Sebum is the largest part of dirt in a wash (Johansson and Somasundaran 2007). Therefore, in this research sebum stain test strips were used to determine cleaning performance. This means that this program is more suitable for washing underwear and shirts.

2. Experimental part

In this study, the influences of parameters on washing performances are obtained through experimental study and the optimum parameter combination is also found.

2.1 Preparation of materials

Sebum stain test strips (GB/T 13174-2008) were purchased from China Research Institute of Daily Chemical Industry, which were cut to $6 \times 6 \text{ cm}^2$ swatches. The thread removal material used (Wang, Zeng et al. 2014) was polyester fabric, whose thread count was 23 ends/cm and 19 picks/cm. The fabric was cut to $5 \times 5 \text{ cm}^2$ pieces. The test load was composed of three cotton shirts and one piece of cotton base load (GB/T 8629-2001), which together was 1/4 of full load. And the size of each piece of cotton base load is $92 \times 92 \text{ cm}^2$. A commercial liquid type detergent (Chaoneng, Nice group Co., Ltd, China) was used. The main ingredients of the detergent included coconut oil soapstock, anionic surfactant, nonionic surfactant and detergent builder. In the experiment, the detergent usage is 20 mL, which is the recommended dosage by the supplier. The washing machine used in the study was a drum-type washing machine (2.8 kg, Xiao Ji Internet Science & Technology Co., Ltd, China) with adjustable parameters. The standard washing machine used was Wascator FOM71 CLS from Electrolux co., Ltd.

2.2 Design of Experiment (DOE) and laundering procedures tested

JMP is a computer program for statistics developed by the JMP business unit of SAS Institute. In this paper, JMP's custom designer is used to design experiment.

(1) Parameters

The aim of this research is to develop a program with lower energy consumption but without increased dosage of chemicals or water consumption. Therefore, the dosage of detergent and bath ratio are fixed parameters. The following parameters are modified: mechanical action (wash speed, on time and off time), wash temperature and main wash duration (the time used to heat up is included in the main wash duration). The detailed parameters and levels are shown in Table 1.

Table 1 Parameters and levels

parameter	temperature	main wash duration	wash speed	on time	off time	dosage of detergent	Bath ratio
(level)	(°C)	(min)	(rpm)	(s)	(s)	(mL)	
high	50	50	58	20	8		
middle	40	35	49	14	14	20	8:1
low	30	20	40	8	20		

(2) Laundering procedures

The laundering procedures designed by JMP's custom design are shown in Table 2.

There are 38 groups in total.

Table 2 Laundering programs of experiment and the test results

laundering program	parameters					indicators		
	temperature	main wash duration	wash speed	on time	off time	detergency	rate of abrasion	energy consumption
	(°C)	(min)	(rpm)	(s)	(s)	(%)	(%)	(kWh)
1	50	20	49	20	20	45.73	17.95	0.336
2	50	35	49	14	14	55.52	19.18	0.361
3	50	20	58	8	20	44.19	14.58	0.313
4	30	50	58	14	8	60.28	21.34	0.136
5	40	35	49	14	8	59.84	21.06	0.244
6	40	35	58	8	14	51.83	16.73	0.244
7	40	50	49	14	20	59.38	18.75	0.226
8	50	50	40	8	20	65.59	16.10	0.325
9	50	50	58	8	8	71.79	20.35	0.337
10	30	20	40	14	8	47.30	17.24	0.113
11	40	50	49	8	14	65.71	18.43	0.237
12	40	20	58	20	20	51.42	15.08	0.209
13	50	20	40	14	14	45.14	16.47	0.320
14	30	50	58	8	20	56.70	15.92	0.099
15	40	35	49	14	14	58.49	16.67	0.228
16	30	20	58	14	20	41.94	13.90	0.108
17	30	20	58	8	8	43.51	19.13	0.111
18	50	50	40	20	8	70.71	20.04	0.319
19	30	35	49	20	8	59.90	23.14	0.140

20	50	35	40	20	14	61.11	22.58	0.320
21	40	35	40	20	20	54.97	19.23	0.231
22	30	35	49	8	20	50.33	17.41	0.133
23	30	50	40	20	20	59.87	21.29	0.124
24	50	20	58	20	8	52.86	18.94	0.321
25	40	35	49	14	14	59.60	20.05	0.241
26	30	20	49	20	14	40.75	17.24	0.122
27	40	20	40	20	8	50.09	19.31	0.219
28	30	50	40	8	8	61.22	19.85	0.109
29	50	50	58	20	20	72.39	21.92	0.368
30	30	35	40	14	20	50.44	18.43	0.134
31	30	20	40	8	14	47.11	15.95	0.102
32	50	20	49	8	8	51.67	16.07	0.317
33	30	50	58	20	14	70.52	22.19	0.150
34	40	50	49	14	14	65.12	18.25	0.219
35	40	35	58	14	14	65.90	19.01	0.242
36	40	20	40	8	20	43.85	14.98	0.217
37	50	35	40	8	8	62.94	18.52	0.305
38	40	35	49	14	14	57.76	20.94	0.229

2.3 Indicators and Measurements

In order to develop an optimized energy-saving procedure, cleaning efficiency, fabric abrasion and energy consumption were measured. The test methods are as follows.

(1) Cleaning performance

Sebum stain test strips were fixed on the wash load before washing. The surface reflectance of the original fabric and the sebum soiled fabrics before and after washing was measured at 4 spots using a WSB-3A intelligent digital whiteness meter (Da Rong, China). In every program, 5 Sebum stain test strips were used. Thus for each washing condition, a total of 20 measurements were averaged. The detergency was calculated using Equation (1), the rate of washing ability was calculated using Equation (2), with reference to GB/T 4288-2008.

$$Dr = \frac{R_w - R_s}{R_o - R_s} * 100\% \quad (1)$$

Where Dr is detergency (%), R_s is the surface reflectance of soiled fabric before washing, R_w is the surface reflectance of soiled fabric after washing, and R_o is the

surface reflectance of the original fabric. In this study, the measured R_o is 76 %.

$$C = \frac{Dr}{Ds} \quad (2)$$

Where C is the rate of washing ability, Dr is the detergency of tested program, Ds is the detergency of the standard washing machine.

(2) Fabric abrasion

The measurement of thread removal polyester material was carried out according to EMPA 304 (IEC PAS 62473-2007). The original and remaining numbers of weft threads, which are shown more sensitive to different programs, were counted to calculate the rate of fabric abrasion. In every experiment, 10 pieces of thread removal material were used. The rate of abrasion was calculated using Equation (3) with reference to IEC PAS 62473-2007.

$$A = \frac{T_o - Tr}{T_o} * 100\% \quad (3)$$

Where A is the rate of abrasion of weft yarns of thread fabric, T_o is original number of weft threads, and Tr is remaining number of weft threads.

The rate of abrasion reflects the mechanical action on fabrics during the washing process. To some extent, the degree of fabric damage can be measured relatively by the rate of abrasion.

(3) Energy consumption

The electric power consumption of every laundering procedure was measured by a powermeter (Christ, Germany) with an accuracy of 1 Wh. The temperature of water inlet was controlled to 20 ± 2 °C for all cycles.

3. Results and discussion

3.1 program optimization

The test results of each designed laundering program were listed in Table 2. The JMP software was used to analyze the data and establish the "Prediction Profiler". The cleaning efficiency, fabric abrasion and energy consumption were determined by the "Prediction Profiler". There is no doubt that required lowest levels of the three indicators have great effect on the optimized combination of parameters. Underwear

and shirts are washed very frequently, so the required cleaning efficiency is not very high. As GB/T 4288-2008 requires, if the rate of washing ability (Equation 2) of a drum washing machine is up to 1.0, this washing machine can be considered to be at level A. This provision in the GB/T 4288-2008 was used for reference in this study. The tested detergency of the “cotton 60 °C” procedure (IEC 60456) of the standard washing machine is 54.07 %. So with reference to this standard and Equation (2), the detergency of the optimized program should at least be 54.07 %. As for the rate of fabric abrasion and energy consumption, the required lowest levels are determined by those of the original program.

Based on the required lowest levels of the three indicators and the aims of lower energy and better washing performance, optimized parameters are determined after establishing the “Prediction Profiler”. The optimized and the original procedures and their predictive results are shown in Table 3.

Table 3 The original parameters and the optimized parameters

parameters	temperature	main wash duration	wash speed	on time	off time	detergency	rate of abarison	energy consumption
(level)	(°C)	(min)	(rpm)	(s)	(s)	(%)	(%)	(kWh)
original	40	27	47	20	15	53.78	19.50	0.2349
optimized	32	35	49	14	14	54.29	19.44	0.1567

Comparing the original and the optimized procedures, energy consumption after optimization is around 1/3 lower than the original, and at the same time, detergency and the rate of fabric abrasion are basically the same as the original.

In order to verify the conclusion, we did five repeated experiments of the two programs, respectively. The results showed there was no significant difference in detergency and fabric abrasion between the optimized and the original programs but the average energy consumption of the optimized was about 37 % lower than the original one. This verified the conclusion.

3.2 energy consumption

It has been found in this research that most of the energy is used to heat the laundering bath, which is also supported by other researches (Mozes, Cornelissen et al. 1998, Janczak, Stamminger et al. 2010, Hauthal 2012, Kim 2015), so lowering the temperature is a priority. In this study, the temperature is lowered to 32 °C from the original 40 °C. The effect of temperature on energy consumption is shown in Figure 3. It is clear that energy consumption is positively related to temperature.

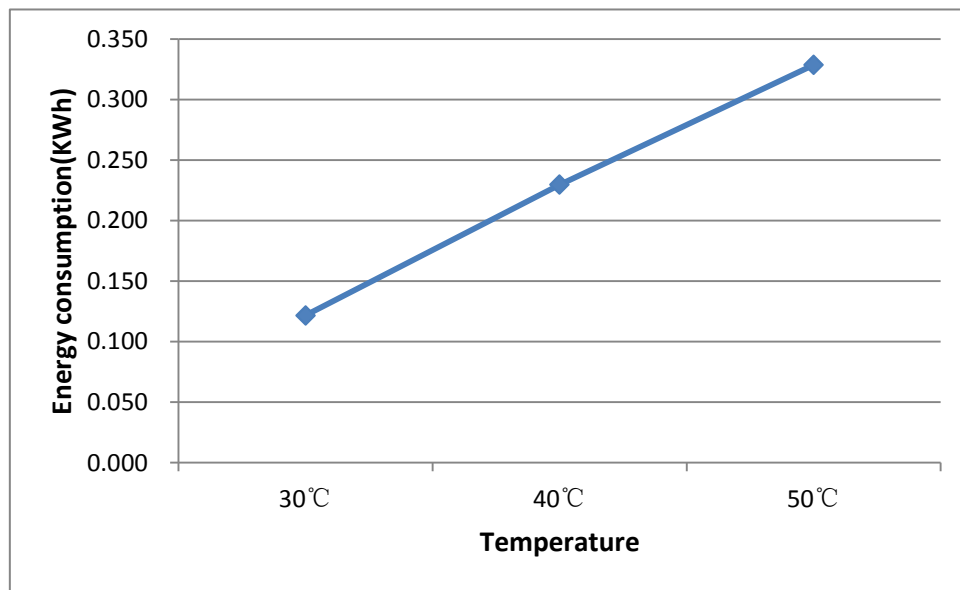


Figure 3 The effect of temperature on energy consumption

3.3 washing efficiency and abrasion performance of laundering procedure

(1) washing efficiency

It seems that the detergency of the optimized program is 0.5 % higher than the original one in Table 3. However, in the “Prediction Profiler”, the root-mean-square error of washing efficiency prediction is 3.06 %. So the detergency of the optimized program is basically the same as the original one. And it is close to level A in GB/T 4288-2008. This standard is used to evaluate household and similar electrical washing machines in China. In this study, it is used for reference only.

For detergency of sebum stain materials, the main controlled factors ranking are main wash duration, temperature and variables related to mechanical action.

Figure 4 shows the effects of different variables on detergency.

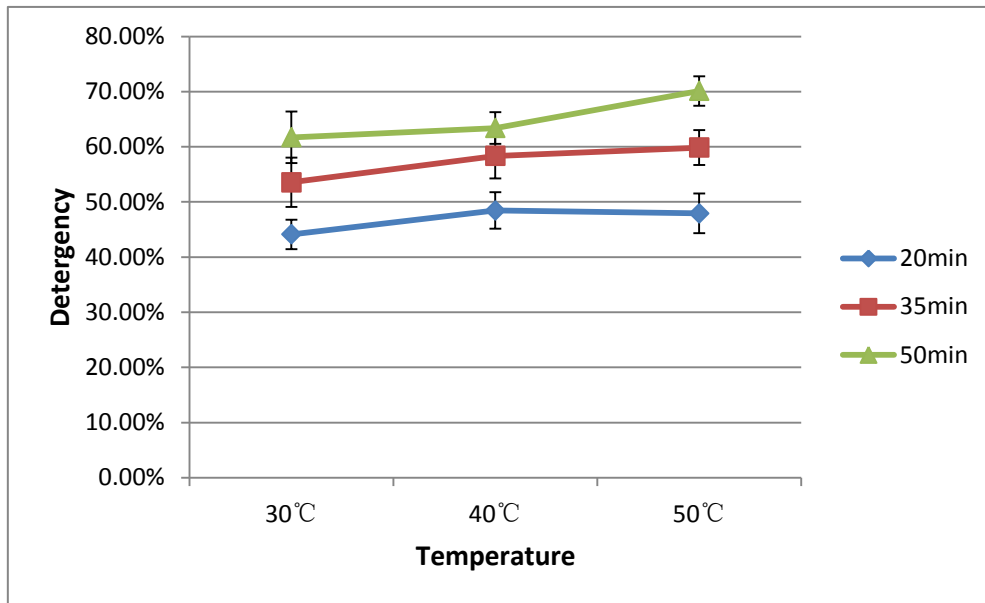


Figure 4 The effect of temperature and main wash duration on detergency

The regression model for cleaning efficiency is shown in Equation (4).

$$Y=0.24868+0.00287*X_1+0.00632*X_2+0.00263*X_3-0.0040*X_4 \quad (4)$$

Where Y is the detergency of sebum soil, X_1 is the wash temperature (°C), X_2 is the main wash duration (min), X_3 is on time (s), X_4 is off time (s). Table 4 shows statistics and ANOVA of the detergency model. F-value is 54.09239 and Prob>F is $4.92939*10^{-14}$. It shows that the model is significant. The adjusted R^2 is 0.852, indicating a good fit for the model .

Table 4 Statistics and ANOVA of the model for cleaning efficiency

	DF	Sum of Squares	Mean Square	F-value	Prob>F
Model	4	0.2541	0.06352	54.09239	$4.92939*10^{-14}$
Error	33	0.03875	0.00117	R-Square	Adj.R-Square
Total	37	0.29285		0.86767	0.85163

From the regression model and Figure 4, it is obvious that the main wash duration is the most important factor influencing the detergency when the dosage of detergent is fixed. With the temperature or main wash time increased, detergency is enhanced. The main wash duration can be prolonged to compensate

for the effect of lower temperature. However, there is a limit as to how long the wash time should be as long wash times are not popular with consumers.

(2) Fabric abrasion

The fabric abrasion rate of optimized procedure is basically the same as the original. In the “Prediction Profiler”, the root-mean-square error of fabric abrasion prediction is 1.22 %.

As expected, parameters related to mechanical action have significant influences on fabric abrasion. The main wash time, on time and off time are important variables. Figure 5 shows the effect of different variables on the rate of fabric abrasion.

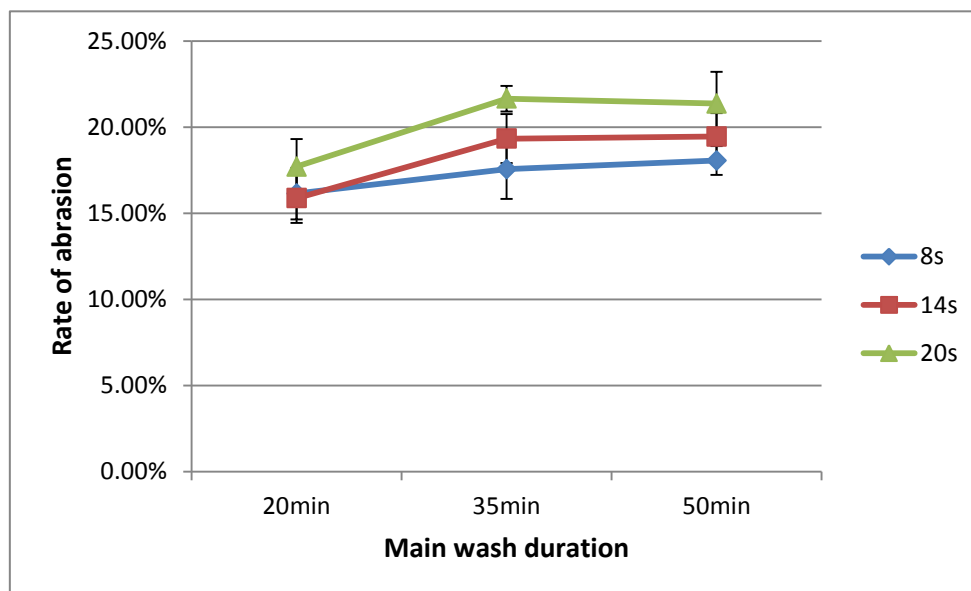


Figure 5 The effect of main wash duration and “on time” on rate of fabric abrasion

In general, the rate of fabric abrasion increases with the increase of main wash duration or “on time”. However, when the main wash duration is 50 min, the rate of abrasion is similar to that when it is 35 min. To some degree, when the washing time is increased to a point, fabric abrasion became stable in this wash load condition. The detailed mechanisms explaining why the rate of abrasion is similar in 35 min and 50 min wash cycles may be studied in the future.

In this study, in order to obtain good cleaning performance and less energy consumption, lowering temperature and prolonging the wash time proved to be effective. However, this can cause higher fabric abrasion. This problem was

solved by lowering the mechanical action appropriately by lowering the “on time” .

3.4 the balance of temperature, duration, mechanical action

The “Prediction Profiler” of different indicators is shown in Figure 6 and the optimized washing condition was determined by adjusting parameters in the “prediction profiler”. By this means, the optimized program achieved the goal, which is lower energy consumption, without lowering the cleaning performance or increasing the fabric abrasion.

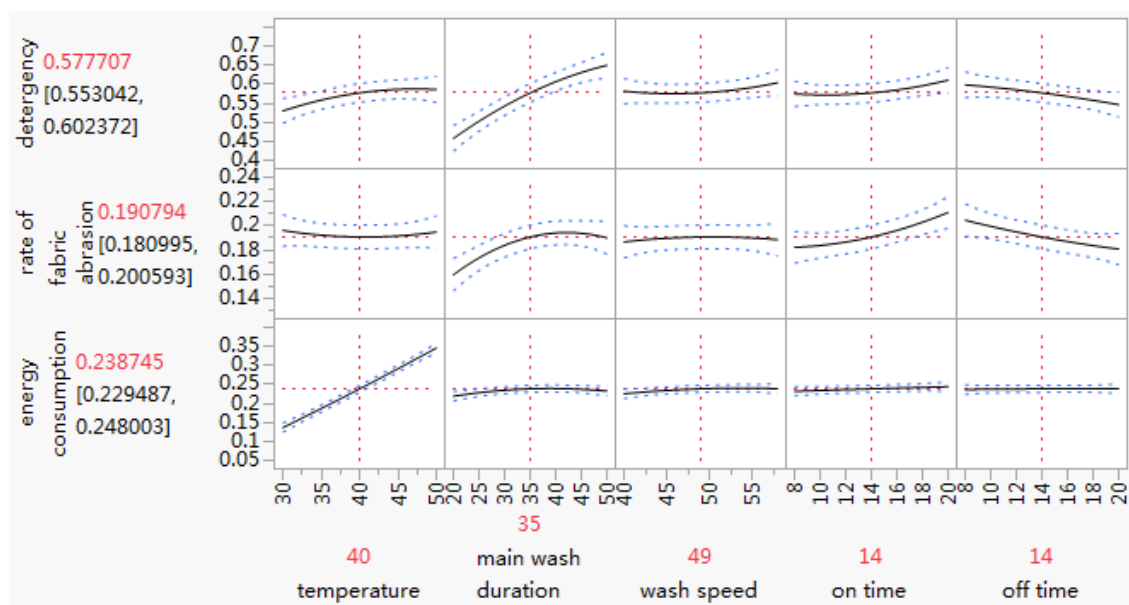


Figure 6 Prediction Profiler

According to the Sinner Circle, a laundering procedure is a result of the synergistic actions between temperature, duration, mechanical action and chemical action, shown in Figure 2 (Hauthal 2012). Achieving a good washing performance requires the optimal contribution of all factors.

In this study, chemical action is a fixed variable. Temperature has an impact on the solubility and Critical Micelle Concentration of a particular type of surfactant (Dave 2015). At high wash temperatures, fatty soils may be melted. Consequently, either they penetrate into fibre making removal difficulty or form mesomorphic phases favouring the ease of removal (Dave 2015). As for mechanical action, it a) maintains uniform detergent concentration throughout the wash liquor, b) provides

energy for the dislodgement of soil from substrate and c) maintains the removed soil in suspension in the wash liquor (Dave 2015). The longer washing time may have helped the stable dispersion of soils that was rolled up or solubilized by detergent solution, contributing to the enhanced overall washing performance (Woo, Kim et al. 2014).

All of the three effects can help the dislodgement of soil from substrate directly or indirectly. Thus, to some extent, higher mechanical action and longer duration at lower wash temperature can make up for the washing efficiency at higher wash temperature, while significantly save the energy consumption. However, considering fabric damage and consumers' duration requirement, a good grasp of degrees need to pay attention.

4. Conclusions

Drum washing machines are more water efficient but more energy-intensive than impeller ones. This study focused on the energy reduction of drum washing machines. In addition, the washing efficiency and fabric abrasion are also considered as they are important performance indicators. We have demonstrated that by optimizing the wash programme, the energy consumption can be reduced and laundering quality unchanged. It is worth mentioning that the amount of water and detergent were kept the same as original.

In this study, the washing program for shirts and underwear was used as an example. The results show that the optimized program can save up to approximately 1/3 of electricity. This finding can help the washing machine manufacturers to optimize washing procedures and it will significantly reduce the environmental impact of washing machines. Further studies are being carried out to examine the optimization of washing programs for other soil and substrate types. In addition, hygienic effects should be considered in the future.

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References

Altenbaher, B., et al. (2011). "Ecological parameters and disinfection effect of low-temperature laundering in hospitals in Slovenia." Journal of Cleaner Production **19**(2): 253-258.

BERTOLDI, P. and B. ATANASIU (2009). "Electricity Consumption and Efficiency Trends in European Union." JRC Scientific and Technical Reports: 14.

Chen, Y. and Y. He (2014). "The practice of sustainable washing practice." China dyeing & finishing(19): 53-55.

Dave, A. (2015). "Physicochemical studies on soiling and soil removal behaviour of textiles."

Fijan, S., et al. (2008). "Implementing sustainable laundering procedures for textiles in a commercial laundry and thus decreasing wastewater burden." Journal of Cleaner Production **16**(12): 1258-1263.

Han, H. R., et al. (2015). "Mechanical and physicochemical contribution in removal of different soil types on cotton fabric." Textile Research Journal **85**(19): 2009-2019.

Hauthal, H. G. (2012). "Washing at Low Temperatures–Saving Energy, Ensuring Hygiene." Tenside Surfactants Detergents **49**(2): 171-177.

Honisch, M., et al. (2014). "Impact of wash cycle time, temperature and detergent formulation on the hygiene effectiveness of domestic laundering." Journal of applied microbiology **117**(6): 1787-1797.

Janczak, F., et al. (2010). "Energy savings by low temperature washing." SÖFW-Journal **136**(4).

Johansson, I. and P. Somasundaran (2007). Handbook for Cleaning/decontamination of Surfaces, Elsevier: 64

Kim, J., et al. (2015). "Comparison of environmental and economic impacts caused by the washing machine operation of various regions." Energy Efficiency **8**(5): 905-918.

Mozes, E., et al. (1998). "Exergy analysis of the conventional textile washing process." Energy conversion and management **39**(16): 1835-1843.

Pakula, C. and R. Stamminger (2010). "Electricity and water consumption for laundry washing by washing machine worldwide." Energy Efficiency **3**(4): 365-382.

Saouter, E. and G. Van Hoof (2002). "A database for the life-cycle assessment of Procter & Gamble laundry detergents." The International Journal of Life Cycle Assessment **7**(2): 103-114.

Wang, F., et al. (2014). "Study on fabric's abrasion during home laundering." China Appliance Technology **12**: 86-89.

Woo, J. H., et al. (2014). "Contributing ratio of the mechanical and the physicochemical actions to washing efficiency of mineral oil and protein soils." Fibers and Polymers **15**(3): 645-652.

Yuan, Z., et al. (2016). "Life cycle assessment of horizontal-axis washing machines in China." The International Journal of Life Cycle Assessment **21**(1): 15-28.