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A Genetic Algorithm for Searching Weaving Parameters for Woven Fabrics

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ABSTRACT

In this study, an intelligent R&D design system is used to obtain the best combination of weaving parameters for woven fabric designs. The searching mechanism, developed in the Turbo C programming environment, and the theory, based on a genetic algorithm, can find several desired solutions of weaving parameters to produce woven fabrics within controlled costs. In addition, the system can simultaneously calculate the fractional cover of the fabric for each set of surveyed solutions in order to provide the designer with options for the functionality of these fabrics. With this system, the weaving mill can integrate the resources of different divisions (*e.g.*, design, production, and financial divisions) to achieve perfect designs for woven fabrics and enhance the enterprise's competitive power.

Before the industrial revolution, textile design was almost wholly controlled by the makers themselves. Moreover, in addition to design, quality control, production management, sales, and marketing were all included. As highly diversified as the modern textile industry has become, such situations seem impossible now. In addition, when designing textiles, one cannot neglect all the information and knowledge related to the manufacturing process in textile engineering. Otherwise, the design work will not go smoothly through all the processes of manufacturing, and quality problems can eventually halt manufacturing.

Recent applications of computer technology in the textile field have spread widely. For example, implementing automation techniques for production processes and management procedures has become increasingly important in textile engineering. Current studies have also investigated applications of computer techniques in the design field [4, 8, 9], *e.g.*, simulation systems for color matching, computer aided design (CAD) systems for static and dynamic states, and semantic color-generating systems for garment design. In this study, we propose an intelligent searching system theory based on a genetic algorithm to search for weaving parameters. There are five weaving parameters, *i.e.*, warp yarn count, weft yarn count, warp yarn density, weft yarn density, and total yarn weight, which are all correlated to one another in weaving. If two or more than two parameters are unknown among them, there will be many available combinations. This study focuses mainly on using the genetic algorithm, which has an excellent searching capacity, to facilitate fabric design to obtain the best combinations of parameters while considering both manufacturing costs and quality.

It is essential for a fabric of good quality to have an appropriate weaving density. If the weaving density is too low, the fabric will obviously be too sparse to have good strength. Yet the higher the weight consumption of material yarns, the higher the manufacturing costs. In the mean time, marketing and sales will become more difficult. On the other hand, lessening the weight of the material yarns can decrease their consumption, but that will damage the good quality of the fabrics. How to strike a good balance between the cost and the essential weight consumption of the material yarns is a key issue, and both cost and quality are taken into consideration in design.

Our system can provide several appropriate combination sets of weaving parameters that can meet a designer's exact demand without the necessity of advance lab-manufacturing. With this system, a fabric designer can efficiently determine what the yarn count and the density of the warp and the weft yarns should be to manufacture the desired width, length, and total weight of the fabric at a pre-controlled cost. Thus, the design, production, and financial divisions can be integrated. Moreover, the fractional cover value, directly related to the air permeability and heat retaining properties of fabrics, can be calculated simultaneously for the designer to refer to when developing novel fabrics. Manufacturers can benefit from the quick response capability provided by this system, and can then enhance their own competitive abilities.

Theory

SEARCHING MECHANISM

The main goal of this study is to explore an effective way to help a fabric designer obtain several appropriate

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combination sets of weaving parameters in a short time. These sets are composed of four variables, warp yarn count, weft yarn count, weaving density of the warp yarn, and weaving density of the weft yarn. We know that the cost of the fabric is directly related to the weight consumption of the material yarns. The more weight consumption, the higher the cost of manufacturing the fabric. In addition, the greater the weight consumption of the material yarns, the heavier the fabric, so much so as to be uncomfortable to wear.

Let's suppose there is a weaving mill that develops a fabric whose total weight consumption is preset as 5.6 $\times$ 10^{-7} (lb) per square inch. For simplification, the shrinkage of the fabric during weaving is neglected. There exist many combinations of weaving parameters (*i.e.*, both yarn count and weaving density of the warp and weft), that can be used for preset weight consumptions of the material yarns. For instance, samples A, B, and C, shown in Table I, all answer these demands. The areas of these three fabric pieces are similar—1 square inch—but they have different yarn counts and weaving densities. Now the question is how a designer can easily and immediately obtain a lot of available combination sets of these four weaving parameters. In other words, it's difficult for a designer to acquire all the possible combination sets of weaving parameters simply through common sense. In addition, in order to speed up the production rate, the weft yarn count used in weaving is usually smaller than the warp yarn count. Thus the weaving density of the warp yarns is usually larger than that of weft yarns during implementation. Sample D's weaving density of warp yarn is smaller than that of its weft yarn. Sample E's warp yarn count is smaller than its weft yarn count. Sample F's weaving density of warp yarn is smaller than its weft yarn, and its warp yarn count is smaller than its weft yarn count. Therefore, Sample D–F shown in Table I are not available for practical use in weaving engineering.

To realize the relationships between these weaving parameters, we have adopted a search method, which is a way to find the maximum or minimum point in a multidimensional space. A genetic algorithm (GA) [1, 2, 5] is a search method based on the mechanism of genetic inheritance. A genetic algorithm maintains a set of trial solutions, called a population, and operates in cycles called generations. Each individual in the population is called a chromosome, representing a solution to the problem at hand. A chromosome is a string of symbols, usually, but not necessarily, a binary bit string.

During each generation, three steps are executed. Step 1: Each member of the population is evaluated and assigned a fitness value, which serves to provide a ranking of the members. Step 2: Some members are selected for reproduction. Step 3: New trial solutions are generated by recombination operators applied to those members, which construct the new population after reproduction. The genetic algorithm is shown in Figure 1, and a brief discussion of the three basic operators of the GA is given next.

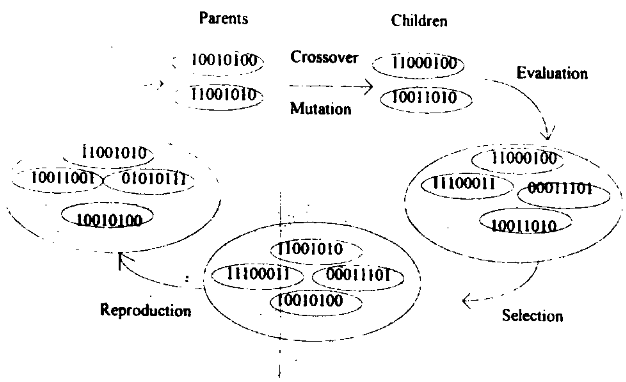


FIGURE 1. Flow chart of genetic algorithm.

TABLE I. Combination sets of weaving parameters for samples A–F.[a]

Samples		N_1, 840 yd/lb		N_2, 840 yd/lb	n_1, ends/in.		n_2, picks/in.	W, lb	Size, width × length
✓	A	1771.6	$N_1 \geq N_2$	885.8	10	$n_1 \geq n_2$	10	5.6×10^{-7}	1 in. × 1 in.
✓	B	1328.8	$N_1 \geq N_2$	1063.0	10	$n_1 \geq n_2$	10	5.6×10^{-7}	1 in. × 1 in.
✓	C	664.4	$N_1 \geq N_2$	531.5	5	$n_1 \geq n_2$	5	5.6×10^{-7}	1 in. × 1 in.
×	D	885.8	$N_1 \geq N_2$	885.8	5	$n_1 < n_2$	10	5.6×10^{-7}	1 in. × 1 in.
×	E	664.4	$N_1 < N_2$	5315.0	10	$n_1 \geq n_2$	10	5.6×10^{-7}	1 in. × 1 in.
×	F	664.4	$N_1 < N_2$	1063.0	5	$n_1 < n_2$	10	5.6×10^{-7}	1 in. × 1 in.

[a] ✓ available for practical application, × unavailable for practical application, N_1, N_2 yarn count of warp and weft yarns, respectively, n_1, n_2 weaving density of warp and weft yarns, respectively, and W total weight of woven fabrics.

GENETIC OPERATORS

Crossover

Crossover is the main genetic operator. It operates on two chromosomes at a time and generates offspring by combining both chromosomes' features. A simple way to achieve crossover would be to choose a random cut-point in one parent chromosome and generate the offspring by combining the segment of one parent to the left of the cut-point with the segment of the other parent to the right of the cut-point, as shown in Figure 2. This genetic algorithm method depends to a great extent on the performance of the crossover operator used.

parents			children	
chromosome 1	10001010	------->	chromosome 1	10011011
chromosome 2	11011011	------->	chromosome 2	11001010

FIGURE 2. Illustration for crossover operation.

Mutation

Mutation is a background operator, which plays a decidedly secondary role in the operation of the genetic algorithm by producing spontaneous random changes in various chromosomes. Mutation is needed because, even through reproduction and crossover effectively search and recombine extant notions, occasionally they may become overzealous and lose some potentially useful genetic material (1's or 0's at particular locations). In artificial genetic systems, the mutation operator protects against such irrecoverable losses. A simple way to achieve mutation would be to alter one or more genes. In genetic algorithms, mutation serves the crucial role of preventing the system from being stuck in the local optimum.

Reproduction

Each set of strings (*i.e.*, chromosome) is evaluated by a certain evaluation function. According to the value of each evaluation function, the number that survives into the next generation is decided for each set of strings. The system then generates sets of strings (*i.e.*, chromosomes) for the next generation.

ENCODING AND DECODING A CHROMOSOME

The domain of variable x_i is $[p_i, q_i]$, and the required precision depends on the number of bits used for encoding. The precision requirement implies that the range of the domain of each variable should be divided into at least $(p_i - q_i)/(2^n - 1)$ size ranges. The required bits (denoted by n) for a variable are calculated as follows, and mapping from a binary string to a real number for variable x_i is straight-forward and completed as follows:

$$x_i = p_i + k_i(p_i - q_i)/(2^n - 1) \quad , \qquad (1)$$

where k_i is an integer between $0\text{–}2^n$ and a so-called searching index. After finding an appropriate k_i to put into Equation 1 to get x_i, which can allow the fitness function to have a fitness value approaching 1, the desired variables can be obtained.

Combine all the variables in a string to become a vector, *i.e.*, $\mathbf{X} = (x_1, x_2, \ldots, x_m)$, and unite all the encoders of the searching index for each variable as a bit string to construct the chromosome shown below:

$$P = b_{11} \ldots b_{1j}\, b_{21} \ldots b_{2j} \ldots b_{i1} \ldots b_{ij} \quad b_{ij} \in \{0, 1\};$$
$$i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n;$$
$$b_{i1} \ldots b_{ij}\text{: the encoded bit string for } k_i \quad . \qquad (2)$$

Suppose that each x_i is encoded by n bits and there are m parameters, then the length of Equation 2 should be an N-bit ($N = m \times n$) string. During each generation, all the searching index k_is of the generated chromosome can be obtained by Equation 3:

$$k_i = b_{i1}{*}2^{n-1} + b_{i2}{*}2^{n-2} + \cdots + b_{in}{*}2^{n-n}$$
$$i = 1, 2, \ldots, m \quad . \qquad (3)$$

Finally, the real number for variable x_i can be obtained from Equations 1 and 3. The flow chart for the encoding and decoding of the parameter is illustrated in Figure 3.

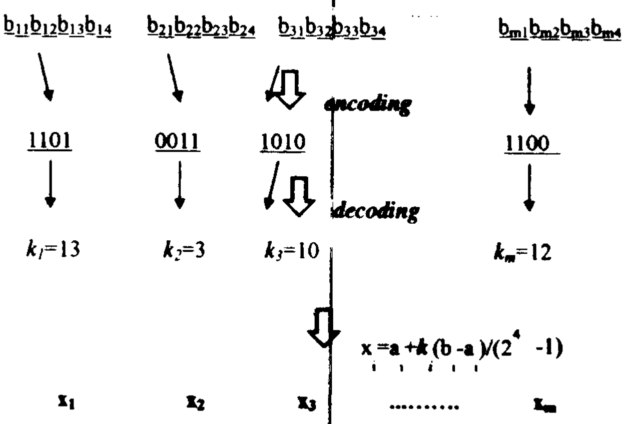


FIGURE 3. Flow chart for encoding and decoding of the parameter with 4-bit precision.

FRACTIONAL COVER

As Figure 4a shows, the fractional cover (denoted by C) [6, 7] can be defined as the fraction of the areas

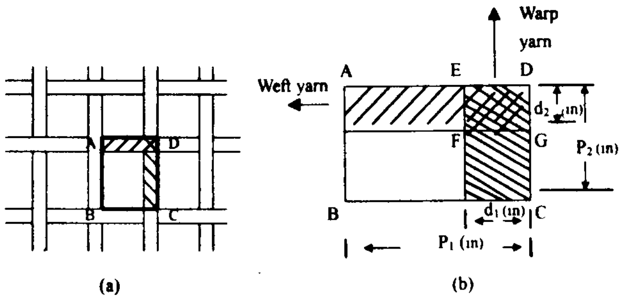


FIGURE 4. Illustration for fractional cover of fabric interlaced with warp and weft yarn: (a) structure of a plain weave, (b) amplified area of rectangle ABCD in a plain weave (d_1, d_2 denote diameters of warp and weft yarns, respectively, p_1, p_2 denote thread spacings of warp and weft yarns, respectively).

covered by the warp and weft yarns and can be acquired by

Covered area by yarns/Rectangular area .

As Figure 4b shows, the total rectangular area (*i.e.*, rectangular area ABCD) can be calculated by $P_1 \times P_2$. The area covered by the warp yarn is $d_1 \times p_2$, and that covered by weft yarn is $d_2 \times p_1$. The entire area covered by the yarns can be obtained by summing the areas covered by the warp and by the weft, but the summation needs to eliminate the duplication area (*i.e.*, rectangular area DEFG $= d_1 \times d_2$) covered by both the warp and weft yarns. Equation 4 can thus calculate the value of the fractional cover of the fabric:

$$C = (p_1 d_2 + p_2 d_1 - d_1 d_2)/p_1 p_2 \quad , \qquad (4)$$

where C is the fractional cover, p_1(in), p_2(in) are the distances between two adjacent yarns in the warp and weft directions, and d_1(in), d_2(in) are the diameters of the warp and weft yarns, respectively.

According to Peirce [6, 7], the derived yarn diameter and the densities of warp and weft yarns can be obtained as $d = 1/(k\sqrt{N})$, $P_1 = 1/n_1$ and $P_2 = 1/n_2$, respectively, and the fractional cover of woven fabrics can be re-formed into Equation 5:

$$C = n_1/(k\sqrt{N_1}) + n_2/(k\sqrt{N_2}) - n_1/(k\sqrt{N_1}) \times n_2/(k\sqrt{N_2}) \quad , \qquad (5)$$

where C is the fractional cover, K ($= 29.28 \sqrt{\text{specific gravity of yarn}}$) is the coefficient varying with the specific gravity of yarn, n_1, n_2 are the weaving densities of the warp and weft yarns (yarns/inch), respectively, and N_1, N_2 are the yarn counts of the warp and weft yarns (840 yd/lb), respectively.

By comparing the fractional cover values, fabric air permeability and heat retaining properties can be approximately evaluated during the design stage. The larger the value of the fabric's fractional cover, the more compact the fabric's structure. Thus, if a fabric lacks air permeability, it has excellent heat retaining properties.

MAXIMUM WEAVING DENSITY

Woven fabrics consist of warp yarns and weft (filling) yarns, which are interlaced with one another according to the class of the structure and the form of the desired design. Each time a warp yarn's position changes from "above" to "below" the weft yarn or from "below" to "above" the weft yarn, there exists an interlacing point. For example, in a plain weave design graph, there are two warp yarns and two weft yarns, which are interlaced with one another in a unit-weave structure, shown in Figure 5b. If these two warp yarns are not crossed by the weft yarn and just laid side by side, as shown in Figure 5a, there will be more warp yarns in the range of 1 inch. The maximum number of warp yarns can be obtained as $1/d$ ends ($d = 1/a$). On the other hand, in a real application, these two warp yarns are supposed to be crossed by the weft yarn. Therefore, a certain space exists between the two yarns because they are being crossed by the weft yarn, which lessens the maximum number of warp yarns available for the range of 1 inch. The number of warp yarns can be calculated as $1/(d' + d)$ ends ($d = 1/a$, $d' = (c/a') \times (1/b)$), as illustrated in Figure 5b. The value of d' represents the average separation distance between two adjacent warp yarns in a unit weave structure, and results from the interlacing points per unit weave structure. The maximum weaving density of warp yarns and weft yarns can thus be obtained as Equations 6 and 7, respectively,

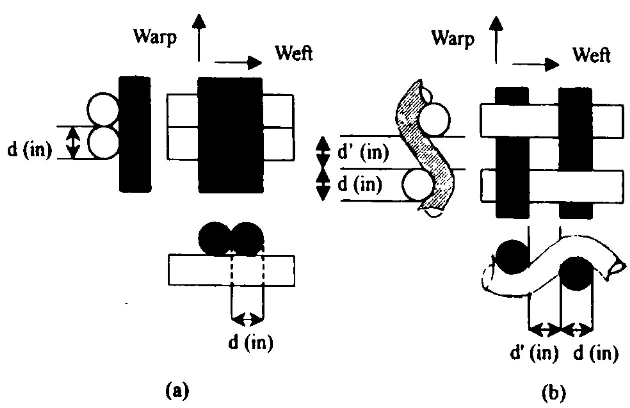


FIGURE 5. Diagram of weave structure: (a) warp and weft yarns are not interlaced with each other, (b) warp and weft yarns are interlaced with each other.

$$X = \frac{1}{(c/a') \times (1/b) + 1/a} = \frac{a \times b \times a'}{b \times a' + a \times c} \quad , \qquad (6)$$

$$Y = \frac{1}{(c'/b') \times (1/a) + 1/b} = \frac{b \times a \times b'}{a \times b' + b \times c'} \quad , \qquad (7)$$

where X(ends/in), Y(picks/in) are maximum weaving densities of the warp and weft yarns, a(ends), b(picks) are the maximum numbers of warp and weft yarns capable of being laid out per inch without crossing, a'(ends), b'(picks) are the number of warp and weft yarns per unit weave structure, and c(points), c'(points) are the number of interlacing points in weft and warp directions per unit weave structure.

Results and System Assessment

IMPLEMENTATION

GA Coding Scheme

The main difference between genetic algorithms and more traditional optimization search algorithms is that genetic algorithms work with a coding of the parameter set and not the parameters themselves. Thus, before any genetic search can be performed, a coding scheme must be determined to represent the parameters in the problem at hand. In finding solutions consisting of proper combinations of the four weaving parameters mentioned earlier, a coding scheme for four item numbers must be determined and considered in advance. A multi-parameter coding, consisting of four sub-strings, is required to code each of the four variables into a single string. In this study, we use a binary coding, and the bit size of encoding for the four variables, *i.e.*, densities of warp and weft yarns and yarn counts of warp and weft, are all set at 4 bits. Thus, a chromosome string consisting of 16 bits can be formed and its layout can be shown as Table II.

Fitness Function

The weight (*i.e.*, W) of a roll of fabric can be obtained by summing the weight of the warp and weft yarns, shown as Equation 8,

$$W = W_1 + W_2 \qquad (8)$$

where

$$W_1 = \frac{n_1 \times L \times \text{Width}}{(1 - S_1) \times N_1 \times 840} \text{ lb and}$$

$$W_2 = \frac{n_2 \times L \times \text{Width}}{(1 - S_2) \times N_2 \times 840} \text{ lb} \quad ,$$

n_1 is the density of the warp (ends/inch), n_2 is the density of the weft (picks/inch); N_1 is the warp yarn count (840 yd/lb), N_2 is the weft yarn count (840 yd/lb), S_1 is the shrinkage of the warp yarn (%), S_2 is the shrinkage of the weft yarn (%), L is the length of the fabric (yd), and Width is the width of the fabric (inches); Equation 8 can be re-formed as follows:

$$W(\text{lb}) = \frac{n_1 \times L \times \text{Width}}{(1 - S_1) \times N_1 \times 840} + \frac{n_2 \times L \times \text{Width}}{(1 - S_2) \times N_2 \times 840} \quad . \qquad (9)$$

The relationship between the required weight of yarns, both densities of warp and weft yarns, both yarn counts of warp and weft, and both length and width of the fabric can thus be determined by Equation 9. The fitness of the GA used in our system is shown in Equation 10. This approach will allow the GA to find the minimum difference between W and W_g when the fitness function value is maximized:

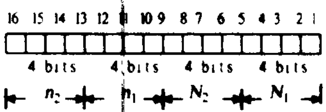
$$\text{Fitness}(W_g) = 1 - \frac{|W - W_g|}{W} \quad , \qquad (10)$$

where W(lb) is the target weight of the yarn and W_g(lb) is the decoded weight of the yarn for each generation.

Necessity to Set Constrained Conditions

Generally speaking, while expecting to increase the production rate, a designer often leaves the weft yarn thicker than the warp yarn. Moreover, the number of

TABLE II. Structure of a chromosome.

Parameter	Gene, bits	Order	Layout of chromosome
Warp count, N_1	4	1–4	
Weft count, N_2	4	5–8	
Warp density, n_1	4	9–12	
Weft density, n_2	4	13–16	

interlacing points will be different depending on the weave structure. There exists a maximum warp or weft weaving density for woven fabrics during weaving [7, 10]. As a practical consideration, the weaving mill always adopts 90% of the maximum weaving density for warp and weft yarns to prevent jammed fabrics, which have a bad hand. In order to make the searching mechanism of the system more realistic and approvable, it is necessary to consider the constrained conditions mentioned above. The conditions that essentially need to be considered during weaving can be illustrated as follows:

$$(1)\ n_1 \geq n_2 \quad , (2)\ N_1 \geq N_2 \quad ,$$
$$(3)\ n_1 \leq X \times 0.9 \quad , (4)\ n_2 \leq Y \times 0.9 \quad ,$$

where X is the maximum weaving density of the warp yarn (ends/inch), Y is the maximum weaving density of the weft yarn (picks/inch), n_1 is the density of the warp (ends/inch), n_2 is the density of the weft (picks/inch), N_1 is the warp yarn count (840 yd/lb), and N_2 is the weft yarn count (840 yd/lb).

If the acquired chromosome's decoded part, such as weaving densities of warp and weft yarns (*i.e.*, n_1, n_2) and yarn counts of warp and weft yarns (*i.e.*, N_1, N_2), is not in accordance with the constrained conditions, it is essential for the system to set the fitness value at zero. Thus, the goal of preventing the system from deriving unfit solutions for the designer during the search is achieved.

Example

In this study, we use our system to search for weaving parameters while the predetermined specifications are set and listed in Table III, *i.e.*, Width = 64 in., Length = 120 yd, Total weight = 58 lb. Based on Equation 9, we can choose a known parameter (*i.e.*, Width, L or W) to set to the left side of the equal sign of the equation. First, we choose the total weight of the material yarn (*i.e.*, W) as an already known parameter and set it to the left side of the equal sign of Equation 9. Second, using a binary coding method, we encode the unknown parameters. Generally speaking, it is not necessary for the number of bits for each variable to be the same. Nevertheless, for simplification, the four unknown parameters are all set at 4 bits in this study. By putting the searching index k_i obtained after processing the genetic algorithm into Equation 1, we can decode and obtain the four weaving parameters, *i.e.*, N_1, N_2, n_1, n_2.

Then, putting these four parameters into Equation 9, we can determine the required weight of the raw material yarns. Using Equation 10, we can compare the calculated weight W_g and the previously set weight W. The smaller the difference between the two, the closer the value of fitness to "1". Thus, a fitness function can be formulated as Equation 10. If the fitness value is close enough to 1, we can decide whether it is necessary to go through more generations or not.

The survey results after ten generations are shown as Table IV. In this instance, if the user is not satisfied with the search result of the best fitness value 0.7531 for the first chromosome for the tenth generation shown in Table IV, he can just reset the generations, say at 20. The same (but it is not necessary to be the same) initial population, crossover probability, and mutation probability of 30, 0.6, and 0.033, respectively, remain, and he can then run the system again to search for another combination of bit

TABLE III. Set target, known conditions, and constrained conditions.

Example	Known condition and set target			Constrained conditions
Searching for weaving parameters	Length (L)	constant	120 yds	(1) $n_1 \geq n_2$ (2) $N_1 \geq N_2$ (3) $n_1 \leq X \times 0.9$ (4) $n_2 \leq Y \times 0.9$
	Width (width)	constant	64 in.	
	Shrinkage of warp yarn (S_1)	constant	6.3%	
	Shrinkage of weft yarn (S_2)	constant	6.3%	where
	Warp yarns per inch (n_1)	variable	60–100 ends/in.	$X = (a \times b \times a')/(b \times a' + a \times c)$ $Y = (b \times a \times b')/(a \times b' + b \times c')$
	Weft yarns per inch (n_2)	variable	60–100 picks/in.	
	Count of warp yarn (N_1)	variable	20–60 Ne	X, Y = maximum weaving density of warp and weft yarns a, b = maximum number of warp and weft yarns capable of being laid out per inch a', b' = number of warp and weft yarns per unit weave structure c, c' = number of interlacing points in warp and weft directions per unit weave structure
	Count of weft yarn (N_2)	variable	20–60 Ne	
	Weight (W)	constant	58 lb	
	Weave structure	constant	plain 1/1	
	Material yarn (Warp/Weft)	constant	cotton/cotton	

TABLE IV. Results of the tenth generation.[a]

Population	Chromosome	N_1	N_2	n_1	n_2	C	Fitness
1	0100010000011100	52.0	22.7	70.7	70.7	0.6946	0.7531
2	0100010000111001	44.0	28.0	70.7	70.7	0.6760	0.6948
3	0100010001011110	57.3	33.3	70.7	70.7	0.6247	0.5640
4	0100010100111001	44.0	28.0	73.3	70.7	0.6835	0.7050
5	0001010101101111	60.0	36.0	73.3	62.7	0.6165	0.5359
6	0100010101001110	57.3	30.7	73.3	70.7	0.6440	0.6029
7	0100010101011111	60.0	33.3	73.3	70.7	0.6275	0.5623
8	0001010100111011	49.3	28.0	73.3	62.7	0.6381	0.6266
9	0100010010010100	30.7	44.0	70.7	70.7	0.6394	0.0000
10	0100010000011100	52.0	22.7	70.7	70.7	0.6946	0.7531
11	0100010001111111	60.0	38.7	70.7	70.7	0.5995	0.5056
12	0001010101001110	57.3	30.7	73.3	62.7	0.6103	0.5590
13	0100110001111111	60.0	38.7	92.0	70.7	0.6314	0.0000
14	0100110001011110	57.3	33.3	92.0	70.7	0.6814	0.0000
15	0100011001101110	57.3	36.0	76.0	70.7	0.6283	0.5532
16	1101011001111111	60.0	38.7	76.0	94.7	0.7036	0.0000
17	0100010001010101	33.3	33.3	70.7	70.7	0.7667	0.0000
18	0100010000011111	60.0	22.7	70.7	70.7	0.6832	0.7226
19	0100010001011010	46.7	33.3	70.7	70.7	0.6451	0.6114
20	0100010000011110	57.3	22.7	70.7	70.7	0.6867	0.7320
21	0100110000011100	52.0	22.7	92.0	70.7	0.7442	0.0000
22	1101110001101110	57.3	36.0	92.0	94.7	0.7529	0.0000
23	0100010001111111	60.0	38.7	70.7	70.7	0.6924	0.0000
24	0100010000011110	57.3	22.7	70.7	70.7	0.6867	0.7320
25	0001011000011011	49.3	22.7	76.0	62.7	0.7117	0.0000
26	0001010100111100	52.0	28.0	73.3	62.7	0.6325	0.6138
27	0100010001111001	44.0	38.7	70.7	70.7	0.6035	0.5428
28	0100010100111111	60.0	28.0	73.3	70.7	0.6538	0.6302
29	0001010101001110	57.3	30.7	73.3	62.7	0.6440	0.6029
30	0100010001111111	60.0	38.7	70.7	70.7	0.5995	0.5056

[a] Population 30, chromosome 16 bits, generation 10, crossover rate 0.6, mutation rate 0.033, N_1 840 yds/lb, N_2 840 yds/lb, n_1 ends/in., n_2 picks/in.

strings. He expects that there exists a chromosome with a better fitness value than 0.7531.

ACCURACY AND EFFICIENCY OF IMPLEMENTATION

With the assistance of this system, many solution sets, consisting of weaving parameters (*e.g.*, N_1, N_2, n_1, n_2), are obtained in a short time to help the designer make a decision more easily when exploring innovative fabrics. Furthermore, the system will figure out the fractional cover (*i.e.*, C) of each solution set depending on the combination of weaving parameters generated after the iterative operation of the GA. For instance, the example shown in Table III, has a GA whose operation conditions of crossover probability, mutation probability, and initial population are set to 0.6, 0.033, and 30, respectively. The results of the tenth generation are shown in Table IV. The decoded value of the ninth chromosome (*i.e.*, 0100010010010100) from right to left per four bits is 30.7 (= N_1, 0100), 44.0 (= N_2, 1001), 70.7 (= n_1, 0100), and 70.7 (= n_2, 0100), respectively. By putting these four decoded values into Equation 5, we can obtain the fractional cover as 0.6394, yet it conflicts with the constrained conditions mentioned above that N_1 (= 30.7) be smaller than N_2 (= 44.0). Thus, the fitness of this solution is set at zero. Among the thirty chromosomes, a fabric designer can easily choose several solution sets, whose fitness values are closer to 1 and are of appropriate fractional cover, from the results shown in Table IV to apply to the R&D of fabric design. Thus, the designer can avoid designing a woven fabric that cannot be manufactured by the production division. Furthermore, the designer can achieve the goal of considering many essential design factors such as cost, functionality (*e.g.*, hand, air permeability, and heat retaining properties, etc.), and the possibility of weaving during the design stage.

SHRINKAGE OF YARNS

Since our goal is to control the total consumption of yarn in the fabric, we must not neglect the shrinkage of warp and weft yarns. It may be possible that different, reasonably good sets of weaving parameters (n_1, n_2, N_1, N_2) result in widely differing shrinkage values S_1 and S_2. Such shrinkage would affect the actual total weight W and thus the relative fitness of the members of the population. Based on Pierce's model of a plain weave [3], we can obtain an equation derived by Pierce as $h/p = (4/3)\sqrt{CR}$, where h $(=(d_1 + d_2)/2)$ denotes crimp height, p $(=1/n)$ denotes thread spacing, and CR denotes crimp ratio. By taking $h = (d_1 + d_2)/2$ (d_1 and d_2 denote the diameters of the warp and weft yarns respectively), $p = 1/n$ (n denotes the weaving density of warp or weft yarn (yarns/in.), and $CR = S/(1 - S)$ (S denotes shrinkage of warp and weft yarns (%)) into the equation $h/p \equiv (4/3)\sqrt{CR}$, we can obtain a reformulated equation, $S = 9 \times n^2 \times (d_1 + d_2)^2/(64 + 9 \times n^2 \times (d_1 + d_2)^2)$. Using this equation, we can estimate the shrinkage of the warp and weft yarns for each solution set generated after the iterative operation of the GA. For instance, the shrinkage in the warp yarn for the first population of the tenth generation (*i.e.*, $N_1 = 52$, $N_2 = 22.7$, $n_1 = 70.7$, $n_2 = 70.7$, $C = 0.6946$, and fitness = 0.7531) presented in Table IV can be estimated as 9.8% by taking $n = 70$, $d_1 = 1/(28\sqrt{N_1}) = 1/(28\sqrt{52})$, and $d_2 = 1/(28\sqrt{N_2}) = 1/(28\sqrt{22.7})$ into the reformulated equation (*i.e.*, $S = 9 \times n^2 \times (d_1 + d_2)^2/(64 + 9 \times n^2 \times (d_1 + d_2)^2)$), and the weft yarn can be estimated as 9.8%. The decoded weight of the first population (*i.e.*, W_g) can be calculated at 45.36 (lb) using Equation 9. Finally, Equation 10 can determine the fitness of the first population to be 0.7821. Comparing the fitness value obtained by the randomly set shrinkage ratio 6.3% used in the example in Table III to that obtained by the estimated 9.8% using Pierce's geometric model, we see that there indeed exists a little difference as expected, for one is 0.7531 and the other is 0.7821. The less accurate the randomly set shrinkage, the more different from the genuine fitness of the population. Therefore it is risky for the designer to randomly set a shrinkage ratio for the warp (*i.e.*, S_1) and weft (*i.e.*, S_2) yarns in the fabrics during the design stage.

In order to make our system more available for practical manufacturing conditions, we are trying to collect gray fabric samples manufactured with various looms and raw material yarns. First, collections are to be divided into several groups according to loom type (e.g., air jet, rapier, gripper, etc.), material yarn ingredients, and fabric structural class to measure the shrinkage ratio of warp and weft yarns. Then, using the statistical regression method, we calculate the respective regression functions for the relationship between fractional cover C and the shrinkage ratio of the warp yarn S_1 (or the weft yarn S_2) in each group. The relation equations about the influence on S_1 and S_2 can thus be simplified and achieved using only C to represent the complicated combination relationships of n_1, n_2, N_1, and N_2, which are highly related to the genuine value of S_1 and S_2 during weaving. Using Equation 5, we can calculate the fractional cover C by each known combination solution set of weaving parameters generated after iterative operation of the GA. Finally, the genuine shrinkage of warp and weft yarns with specific manufacturing conditions can be estimated by using each respective calculated regression function (consisting of C and S_1, or S_2) instead of just being randomly set at a certain constant such as 6.3% by the designer for warp and weft yarns in the example shown as Table III.

Conclusions

In this study, we have successfully set up a searching mechanism based on a genetic algorithm for efficiently finding appropriate combination sets consisting of weaving densities and yarn counts of material warp and weft yarns to be used in manufacturing. The searching mechanism of the design system has an excellent search capacity to allow the fabric designer to obtain the best combinations of weaving parameters during manufacturing, considering costs. In addition, by integrating our R&D design system with the commercialized computer aided design system for weave structure, it becomes possible for designers to display the profile of the woven fabric from the weaving parameters surveyed by the GA directly on the monitor to enhance convenience and efficiency during design. The entire system of the design, production, and financial divisions of a company can thus be integrated.

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