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Raw material and waste balance in the production of an antistatic combined yarn: mass and value analysis and substantiation of machine requirements

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Abstract. In antistatic combined yarns, only the cotton component passes through all preparatory stages of a spinning mill, whereas the far more expensive conductive multifilament is introduced at the ring frame. Mass-based waste balances must therefore be built for the cotton fraction and miss the economic weight of the waste. This study develops a raw material and waste balance, in mass and value terms, for a 24 tex combined yarn of cotton (77 %) and the conductive multifilament Nega-Stat® P210 (23 %) produced on a carded ring-spinning line. Allocating the waste norms to the processing stages gives total returns and waste of 11.11 % and a yarn yield of 88.89 % for the cotton component, and 2.53 % waste for the multifilament. A balance equation that accounts for in-house recycling of sliver and roving returns raises the yarn yield on fresh cotton to 90.02 %. Draft-in coefficients (77.0–82.8), stage outputs for 120 kg/h of yarn and the machine set are substantiated. Producing 100 kg of yarn consumes 86.6 kg of cotton mix (85.5 kg of fresh cotton when returns are recycled) and 23.6 kg of multifilament, i.e. a material utilisation of 90.7 % (91.7 % on fresh raw material). Multifilament waste is 16 times smaller than cotton waste by mass but 3.1 times larger by value; reducing it by 1 percentage point saves about 0.45 million BYN per year, 12.4 times more than the same reduction for cotton. Separate collection and hydrometallurgical silver recovery are proposed for future silver-coated components.

Keywords: combined yarn; waste balance; draft-in coefficient; material utilisation; value-weighted waste; machine requirement; silver recovery

1. Introduction

Raw materials account for the largest share of production costs in light-industry enterprises, and the rational use of raw materials together with waste reduction is therefore one of the main directions of resource saving [1–4]. In spinning, the yields of intermediate products and the waste balance determine raw material consumption, the quantity of material that has to be processed at each stage and, ultimately, the number of machines required [5, 6]. Textile waste recycling and the principles of the circular economy additionally require waste to be classified not only by quantity but also by quality and value [2].

Electrostatic discharges from clothing and from the human body are a recognised ignition source in explosion- and fire-hazardous industries [7], and protective

clothing for such workplaces must meet the electrostatic requirements of EN 1149-5 [8]. The most common way of achieving the required surface resistance is to integrate electrically conductive fibres or yarns into the textile structure [9]. In a combined (core-spun) yarn, a conductive multifilament is combined with a cotton drafted strand on the ring spinning frame, so that the comfort of cotton and the humidity-independent conductivity of the multifilament are united in one yarn [10, 11]. Research on filament-core and metal-wire core-spun yarns has concentrated on yarn structure and properties: core coverage and resistance to core stripping [12], and tensile behaviour, bending rigidity and hairiness [13]. The raw material and waste economics of such yarns, which directly affect the cost of antistatic workwear fabrics, have received much less attention.

For combined yarns, the balance calculations have specific features. The cotton component passes through all stages from opening and cleaning to roving, whereas the electrically conductive multifilament is introduced only at the ring spinning frame [10, 11]. The stage-wise balance and the draft-in coefficients must therefore be built for the cotton fraction of the combined yarn rather than for the whole yarn. Moreover, because the conductive component is many times more expensive than cotton, a conventional mass balance does not reflect the economic significance of the waste. In managerial cost accounting, spoilage is costed by the resources consumed in producing it rather than measured by its physical quantity [14], but this principle has not been applied to waste norms in combined-yarn spinning. Finally, a transition to silver-coated metal-organic multifilaments, which are commercially available as fine polyamide yarns [15], would add the question of recovering the precious metal from the waste.

To the best of our knowledge, no published waste balance simultaneously accounts for components that enter the process at different stages, for in-house recycling of returns and for the very different unit values of the components. The aim of this study was therefore to analyse the raw material and waste balance for producing a 24 tex antistatic combined yarn in mass and value terms and to substantiate the draft-in coefficients and the number of machines. The specific objectives were to allocate the carded-system waste norms to the processing stages of the cotton component, to derive a balance equation that accounts for recycled returns, to determine the draft-in coefficients and machine numbers for the target output, to compare the mass and value structure of the waste and its cost sensitivity, and to outline the chemistry of silver recovery from the waste of silver-coated components. The novelty of the work is a waste balance model for a combined yarn that takes into account both the recycling of returns and the value of the components.

2. Materials and methods

2.1. Yarn and process line

The 24 tex combined yarn consisted of an 18.4 tex cotton component (mass fraction $\beta = 0.77$) and a 5.6 tex Nega-Stat® P210 conductive multifilament (mass fraction 0.23) [16]. The technology of introducing the conductive component at the spinning stage had previously been tested on other equipment [17]. The process line comprised a

Rieter blowroom line, a C60 card, two passages of RSB-D40 draw frames, a Zinser 668 roving frame and a G35 ring spinning frame [18]. Because the multifilament is fed only at the ring frame, all preparatory stages process cotton alone.

2.2. Waste norms and balance equations

The norms for the yields of yarn, returns and waste were adopted for the carded spinning system and allocated to the processing stages. Sliver waste was assigned only to the stages at which sliver is handled (carding, drawing and roving), whereas drafted-strand (pneumafil) waste, yarn rings and hard yarn waste were assigned only to the spinning stage. Returns are sliver and roving waste that is fed back into the mix within the mill; all other items were treated as waste. The yield of intermediate product at stage *i* was determined from the cumulative returns and waste of all stages up to and including that stage:

$$B_i = 100 - \sum_{j=1}^{i} w_j , \qquad (1)$$

where B_i is the intermediate product yield at stage *i*, % of the mix mass, and w_j is the returns and waste at stage *j*, % of the mix mass.

The draft-in coefficient (intermediate product requirement per 100 kg of yarn) gives the mass of cotton intermediate product that must be produced at each stage to obtain 100 kg of combined yarn:

$$K_{d,i} = \frac{B_i \beta}{B_y} \cdot 100, \qquad (2)$$

where B_y is the yarn yield on the cotton component, %, and β is the mass fraction of cotton in the combined yarn. When the returns (sliver and roving waste, fraction *r*) are fed back into the mix, the consumption of fresh cotton F and the mass of the mix m_{mix} are related by $F = m_{mix}(1 - r)$. Since the yarn yield on the mix is B_y, the yarn yield on fresh cotton is

$$B_y^{fresh} = \frac{B_y}{1 - r}. \qquad (3)$$

2.3. Hourly stage outputs and machine requirements

The quantity of intermediate product to be processed per hour at stage *i* and the required number of machines were calculated as

$$G_i = \frac{G K_{d,i}}{100}, \qquad (4)$$

$$M_i = \frac{G_i}{H_i}, \qquad (5)$$

where G is the hourly yarn output of the spinning department, kg/h, and H_i is the planned output of one machine, kg/h, i.e. the product of the output norm and the running-machine coefficient. For the card, the output norm was based on the corrected machine efficiency coefficient $\eta = K_a \cdot K_b = 0.937$, the product of the partial

coefficients K_a and K_b. The output of the spinning department was set by the number of ring frames.

2.4. Value assessment and sensitivity analysis

The waste was valued at 2020 prices: 5.1 BYN/kg for cotton and 255 BYN/kg for Nega-Stat® P210. Since prices change over time, the value indicators are used for a relative comparison of the components rather than as absolute costs. The sensitivity of raw material costs to waste reduction was assessed by lowering the waste norm of each component by 1 percentage point and calculating the resulting change in raw material consumption per 100 kg of yarn and, for the annual output of 732.8 t adopted in the companion techno-economic study, the annual saving.

3. Results

3.1. Stage-wise waste balance of the cotton component

The balance of returns and waste for the cotton component is given in Table 1. The column totals give the stage losses, and the bottom row gives the intermediate product yield calculated by Eq. (1).

Table 1. Stage-wise balance of returns and waste for the cotton component, % of the mix mass

Returns and waste	Total	Blowroom line	Carding	Drawing I	Drawing II	Roving	Spinning
Sliver waste	0.94	–	0.282	0.235	0.235	0.188	–
Roving waste	0.32	–	–	–	–	0.16	0.16
Drafted-strand (pneumafil) waste	1.78	–	–	–	–	–	1.78
Yarn rings	0.10	–	–	–	–	–	0.10
Motes and fly (blowroom)	3.23	3.23	–	–	–	–	–
Card motes and fly	1.21	–	1.21	–	–	–	–
Card flat strips	1.74	–	1.74	–	–	–	–
Clean sweepings	0.14	–	0.03	0.015	0.003	0.03	0.06
Soiled sweepings	0.15	0.15	–	–	–	–	–
Hard (tangled) yarn	0.1	–	–	–	–	–	0.10

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Returns and waste	Total	Blowroom line	Carding	Drawing I	Drawing II	Roving	Spinning
waste	0						
Fly from rollers and clearers	0.10	–	0.01	0.02	0.02	0.02	0.03
Other waste	0.30	0.30	–	–	–	–	–
Invisible loss	1.00	0.75	0.25	–	–	–	–
Total	**11.11**	**4.43**	**3.52**	**0.27**	**0.26**	**0.40**	**2.23**
Intermediate product yield B_i	–	95.57	92.05	91.78	91.52	91.12	88.89

The total returns and waste of the cotton component amount to 11.11 % of the mix mass, and the yarn yield on the cotton component is 88.89 %. For the electrically conductive multifilament, waste arises only at the spinning stage; its norm is 2.53 %, which corresponds to a yield of 97.47 %. The distribution of the cotton waste over the processing stages is shown in Fig. 1a: 71.6 % of the cotton waste is generated at the opening–cleaning (blowroom) and carding stages, whereas the two drawing passages and the roving frame together contribute less than 1 % of the mix mass.

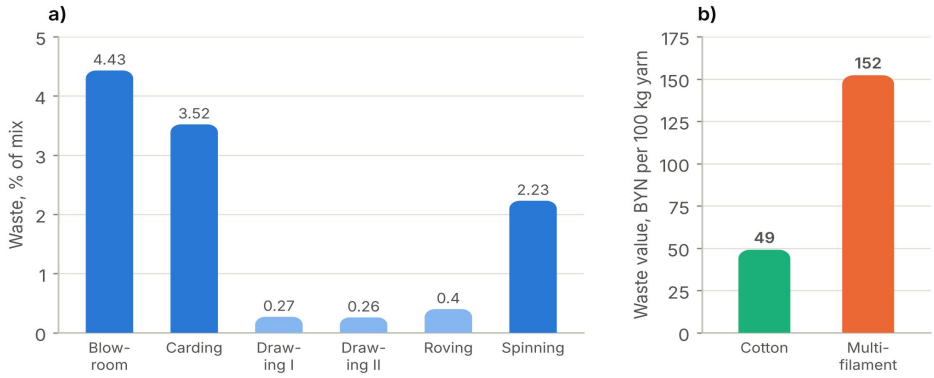


Figure 1. Waste of the combined yarn: a) distribution of the cotton-component waste over the processing stages, % of the mix mass; b) value of the waste per 100 kg of combined yarn, BYN

3.2. Balance with recycled returns

The returns (sliver and roving waste) amount to r = 1.26 % and are fed back into the mix within the mill. According to Eq. (3), the yarn yield on fresh cotton is 88.89/(1 − 0.0126) = 90.02 %. Consequently, the consumption of fresh cotton per 100 kg of yarn is 77/0.9002 = 85.5 kg, whereas the mass of the mix that has to be processed remains 86.6 kg (Section 3.4). Recycling of returns thus reduces the purchase of fresh fibre without changing the material flow through the preparatory stages, which is why the mix mass, not the fresh cotton mass, was used to calculate the draft-in coefficients.

3.3. Draft-in coefficients and machine requirements

With four G35 ring frames (4,800 spindles) and a planned spindle output of 0.025 kg/h, the hourly yarn output is G = 4,800·0.025 = 120 kg/h. The draft-in coefficients calculated by Eq. (2), the hourly stage outputs and the machine numbers are listed in Table 2.

Table 2. Draft-in coefficients, hourly stage outputs and machine numbers

Stage	B_i, %	K_d	G_i, kg/h	H_i, kg/h	M_i, calculated	Adopted
Blowroom line	95.57	82.8	99.4	848.4	0.12	1 (load 0.12)
Carding (C60)	92.05	79.7	95.7	85.6	1.12	1*
Drawing I (RSB-D40)	91.78	79.5	95.4	197.9	0.48	1 (load 0.48)
Drawing II (RSB-D40)	91.52	79.3	95.1	197.9	0.48	1 (load 0.48)
Roving (Zinser 668)	91.12	78.9	94.7	90.3	1.05	1*
Spinning (G35)	88.89	77.0	120.0 **	30.05	3.99	4

* The output must be increased by 12 % (card) and 5 % (roving frame), respectively (see Section 4.2). For the card, the output norm was based on the corrected machine efficiency coefficient $\eta = K_a \cdot K_b = 0.937$.

** For the spinning stage, G_i is the mass of the combined yarn (of which the cotton component is $G \cdot K_d/100 = 92.4$ kg/h).

The draft-in coefficient decreases from 82.8 at the blowroom line to 77.0 at the spinning stage, so that between 99.4 and 94.7 kg of cotton intermediate product must be processed per hour at the preparatory stages. For the card, the corrected planned output H = 85.6 kg/h gives M = 1.12. The adopted set comprises one blowroom line, one card, one draw frame per passage (each loaded at 48 %), one roving frame and four ring spinning frames; the card and the roving frame require an output increase of 12 % and 5 %, respectively.

3.4. Raw material consumption and waste composition

Since 100 kg of combined yarn contain 77 kg of cotton and 23 kg of multifilament, the raw material consumption is $G_p = 77/0.8889 = 86.6$ kg of cotton mix and $G_k = 23/0.9747 = 23.6$ kg of multifilament. The material utilisation coefficient is 100/(86.6 + 23.6) = 90.7 %; when the returns are recycled, it amounts to 100/(85.5 + 23.6) = 91.7 % on fresh raw material. Per 100 kg of yarn, the cotton waste amounts to 9.62

kg and the multifilament waste to 0.60 kg. The distribution of the cotton waste according to its possible use is given in Table 3.

Table 3. Cotton waste per 100 kg of combined yarn, grouped by possible use

Group	Composition	% of the mix	kg per 100 kg of yarn
Returns (recycled in-house)	Sliver and roving waste	1.26	1.09
Spinnable waste	Drafted-strand (pneumafil) waste, yarn rings, card flat strips, hard yarn waste	3.72	3.22
Low-grade waste	Motes and fly, sweepings, other waste	5.13	4.44
Invisible loss	–	1.00	0.87
Total		**11.11**	**9.62**

Low-grade waste is the largest group, followed by spinnable waste.

3.5. Mass versus value of the waste

The mass and value indicators of the waste are compared in Fig. 1b and Table 4.

Table 4. Mass and value indicators of the waste per 100 kg of combined yarn

Component	Waste, kg	Mass share, %	Raw material price, BYN/kg	Waste value, BYN	Value share, %
Cotton	9.62	94.1	5.1	49	24.4
Multifilament	0.60	5.9	255	152	75.6
Total	10.22	100	–	201	100

The multifilament waste is 16 times smaller than the cotton waste by mass but 3.1 times larger by value. In other words, the mass and value structures of the waste are almost mirror images: cotton accounts for 94.1 % of the waste mass but only 24.4 % of its value, whereas the multifilament accounts for 5.9 % of the mass and 75.6 % of the value.

3.6. Sensitivity to a reduction of the waste norms by 1 percentage point

Reducing the multifilament waste norm from 2.53 to 1.53 % lowers the multifilament consumption by 0.24 kg (61 BYN) per 100 kg of yarn; at the annual output of 732.8 t this corresponds to about 0.45 million BYN. For comparison, increasing the yarn yield on the cotton component by 1 percentage point (from 88.89 to 89.89 %) lowers

the cotton consumption by 0.96 kg (4.9 BYN) per 100 kg of yarn, i.e. the annual effect is only 0.036 million BYN (Table 5).

Table 5. Effect of reducing the waste norm of each component by 1 percentage point

Indicator	Cotton component	Multifilament
Waste norm, % (base → new)	11.11 → 10.11	2.53 → 1.53
Raw material consumption, kg/100 kg of yarn (base → new)	86.62 → 85.66	23.60 → 23.36
Raw material saving, kg/100 kg of yarn	0.96	0.24
Saving, BYN/100 kg of yarn	4.9	61.1
Annual saving (732.8 t), thousand BYN	36	448

A reduction of the multifilament waste by 1 percentage point is therefore 12.4 times more effective than the same reduction of the cotton waste. It follows that priorities in waste management should be set by value rather than by mass. For this purpose, a value-weighted waste indicator can be used:

$$W_v = \sum_i w_i \, c_i, \qquad (6)$$

where w_i is the waste of the i-th component, kg (per 100 kg of yarn), and c_i is the price of that component, BYN/kg. For the yarn studied, W_v is the total waste value given in Table 4.

4. Discussion

4.1. Sources of the cotton waste

The balance shows that most of the cotton waste is generated at the blowroom and carding stages (4.43 % and 3.52 %). This waste consists mainly of motes, fly and card flat strips; its amount is determined by the fibre quality and the cleaning intensity, and its reduction is a compromise between cleaning efficiency and fibre damage [5, 18]. The distribution thus reflects the role of the blowroom and the card as the principal cleaning stages of the carded system rather than a feature of the combined yarn. Assigning sliver waste only to the stages that handle sliver makes the sum over the stages consistent with the sum of the waste norms (11.11 %). The invisible loss (1.00 %) is related mainly to moisture loss of the fibres and to fine fibrous dust carried away with the air at the blowroom and carding stages; because cotton is hygroscopic, this loss can be reduced by keeping the relative humidity in the mill stable [6].

At the spinning stage, both the cotton waste (2.23 %) and the entire multifilament waste arise. The largest cotton item at this stage is drafted-strand (pneumafil) waste

(1.78 %), which is formed at end breaks; since end breaks and their repair also generate multifilament remnants, measures that reduce the end-breakage rate act on both components at once.

4.2. Machine utilisation

With respect to machine numbers, the blowroom line and the draw frame of each passage have a considerable reserve (loads of 12 % and 48 %, respectively). It is possible to perform both drawing passages on a single machine, but its load would then reach 96 % and no reserve would remain; one draw frame per passage, each loaded at 48 %, was therefore adopted. The low loads are a direct consequence of the combined-yarn technology: the conductive component is introduced only at the spinning stage, so the preparatory stages process only the cotton fraction, i.e. 77 % of the yarn mass.

At the carding and roving stages, the calculated machine numbers slightly exceed one (1.12 and 1.05). If a single machine is adopted at each of these stages, the delivery speed of the card has to be raised from 300 to 330 m/min together with an increase in its time-utilisation coefficient, and doffing on the roving frame has to be automated; otherwise, a second card has to be installed and operated at partial load. Because the speed increase alone does not fully cover the required 12 %, the card is the bottleneck of the line, and measures that raise its time-utilisation coefficient are the most valuable.

4.3. Value-based waste management

The value analysis reveals the main limitation of the traditional mass balance: in combined-yarn production, 75.6 % of the waste value is attributable to the multifilament waste, which represents only 5.9 % of the waste mass. The main reserve of resource saving is therefore to minimise multifilament remnants during package changes and the repair of end breaks, to increase the package mass and to control the degree to which packages are unwound before replacement. This priority strengthens as the price of the multifilament increases: with metal-organic components such as silver-coated polyamide, the share of the multifilament in the waste value will grow further.

These findings extend the existing literature on the literature on filament-core and metal-wire core-spun yarns, which evaluates mainly yarn structure and mechanical properties [12, 13], by showing that for antistatic combined yarns the material economics are dominated by the minor, expensive component. In line with cost-accounting practice, where spoilage is costed by the resources consumed in producing it [14], the value-weighted indicator of Eq. (6) allows waste norms and process improvements for components of very different value to be compared on a common basis. Process optimisation studies of combined yarns should therefore include the multifilament waste as a response alongside yarn quality indicators.

4.4. Separate collection and silver recovery

Waste of a metallised component should be collected separately, because it contains a precious metal and because metal particles act as contaminants when mixed cotton waste is regenerated. A conventional hydrometallurgical route for recovering silver

consists of dissolving the metal in nitric acid, precipitating silver as the chloride and reducing it to the metal [19]:

$$3Ag + 4HNO_3 \rightarrow 3AgNO_3 + NO\uparrow + 2H_2O \quad (7)$$

$$AgNO_3 + NaCl \rightarrow AgCl\downarrow + NaNO_3;\ 2AgCl + Zn \rightarrow 2Ag + ZnCl_2 \quad (8)$$

Because polyamide is partially degraded by nitric acid, the possibility of reusing the polymer fraction is limited; for such waste, a scheme in which silver is recovered first and the polymer residue is disposed of afterwards is therefore appropriate. Waste of the Nega-Stat® P210 multifilament, which has a carbon-containing conductive core [16], contains no precious metal and can instead be directed to mechanical recycling together with polyester waste. The use of the cotton waste depends on its quality: returns are recycled within the mill, spinnable waste can be regenerated for condenser spinning or nonwovens, and low-grade waste can be used for composite materials and technical wadding [2].

4.5. Limitations

The waste norms were adopted as normative values for the carded spinning system, and the value assessment is based on 2020 prices. The balance is deterministic and does not reflect variations in fibre quality, and the silver recovery scheme is based on established chemistry rather than on experiments with yarn waste. The norms therefore need to be verified under production conditions and the value indicators recalculated at current prices.

5. Conclusions

1. The stage-wise waste balance of the cotton component was refined: total returns and waste amount to 11.11 % and the yarn yield to 88.89 %; when the returns are recycled, the yarn yield on fresh cotton is 90.02 %; the multifilament waste is 2.53 %.
2. The draft-in coefficients were determined (blowroom line 82.8; carding 79.7; drawing I 79.5; drawing II 79.3; roving 78.9; spinning 77.0). For an output of 120 kg/h of yarn, one blowroom line, one card, one draw frame per passage (load 48 %), one roving frame and four ring spinning frames are required; the output of the card and the roving frame has to be increased by 12 % and 5 %, respectively.
3. Producing 100 kg of yarn consumes 86.6 kg of cotton mix (85.5 kg of fresh cotton when returns are recycled) and 23.6 kg of multifilament; the material utilisation coefficient is 90.7 % (91.7 % on fresh raw material).
4. The multifilament waste represents 5.9 % of the waste mass but 75.6 % of its value; reducing it by 1 percentage point saves about 0.45 million BYN per year, so waste management priorities should be set by value rather than by mass.
5. For a transition to silver-coated components, separate collection of their waste and hydrometallurgical recovery of silver were proposed.

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