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Textile Development (TED) Method – a new method for the sustainable development of new textile products

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ABSTRACT

The textile field is diverse and encompasses products intended for technical and non-technical applications. The product diversity in the textile domain has led to various product development approaches. This paper describes a product development method for textile products that is generally applicable. In the so-called Textile Development (TED)-Method, the textile surface manufacturing process is determined in the product development process. In this way, it is possible to develop in an open, target-oriented way and independent of an existing supplier or machine park. By using correlation matrices, a broad design field is considered and specific solutions are extrapolated that lead to the desired product without lengthy iteration series. Thus, the TED-Method additionally represents a resource-saving product development without renouncing a broad design field. Three different development examples of the TED-Method are presented, thus demonstrating the open and comprehensive use of the method.

Keywords
product development,
methodology,
textile product,
technology selection,
pattern selection

1 Introduction

Textiles, especially technical textiles, are used in many applications and products. Applications range from clothing and specialised clothing such as sportswear and protective clothing, to home textiles, various technical textiles such as filters, nets and medical implants to reinforcing structures in composites. Unlike in classical product development, the (mechanical) behaviour of textile products is not only determined by the "material" and the product shape, but also decisively by the yarn properties, the textile manufacturing method and its structure or design.

The VDI 2221 guideline [1] is an example of a conventional, systematic, and structured approach to product development [2]. Due to the wide range of possibilities and the high influence of "material selection" in the development of textile products, product development methods such as VDI 2221 are only used at a later stage in textile product development. Product development models such as VDI 2221 or the V-model [3] follow the general structure of product development processes (Fig. 1). First, suitable requirements for the product are generated. How these requirements are generated is partly defined in the different processes. This requirement generation is followed by a guideline for the development, construction and/or validation of the product. At the end of the product development process there is a final product.

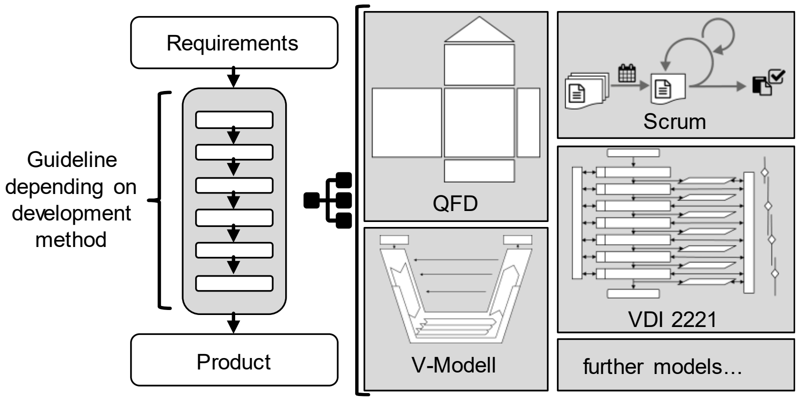

Fig. 1 General structure of product development processes; QFD – Quality Function Deployment [1,3-5]

Typical for a textile product development is a strong correlation of design, yarn material and the possibilities of the yarn-forming machine, the fabric-forming machine as well as the finishing process. These special features cannot be represented by general product development methods. Unlike the selection of a solid material as in metal processing, when developing a textile product with complex properties, the selection of the textile material, for example, is not solved with "a fabric" or "polyester yarn" (Fig. 2). Rather, the choice and development of the yarn and textile design in particular is already part of the product development process. For this reason, the development of new design patterns in textile technology is a time-consuming and iterative process in which the various prototype pieces are regularly reviewed and approved by the designer [6].

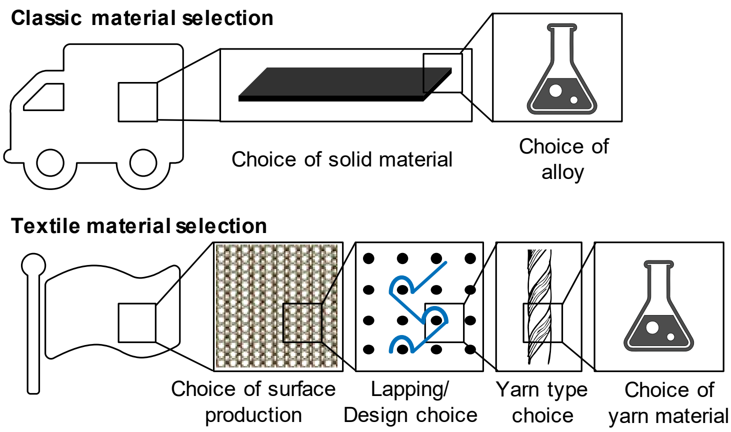

Fig. 2 Comparison of classic and textile material selection.

In textile product development, first of all, the textile surface manufacturing process and usually also the lapping or pattern of the surface manufacturing process are determined. If the lapping has not yet been determined at the time of product development, elaborate, iteration-rich test series have to be carried out. This procedure is neither sustainable nor resource-saving. At the same time, possible solutions are often not considered due to time and monetary constraints. There are various textile product development methods that are either adapted to a surface manufacturing technology or a specific product. There is a lack of a product development method that focused on determine the surface manufacturing, lapping and other machine setting parameters.

2 Methods

First, to identify existing product development methods across the textile domain, a scoping review is conducted. To conduct the review, the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020 scoping review checklist [7] is observed. The results of the scoping review are analysed. Subsequently, an alternative product development method, the Textile Development (TED) Method, is presented in this chapter. The TED-Method focus on the manufacturing process and the lapping or pattern of the surface manufacturing process. Therefore, elaborate, iteration-rich test series have not to be carried out. Because of this the TED-Method is a sustainable and resource-saving alternative to traditional textile product development.

2.1 Existing textile product development methods

The PRISMA method is a 27-item checklist to conduct a transparent and systematic review [7]. By conducting the PRISMA method, thirty-seven product development process models are identified from forty-nine selected documents via a content review. The product development methods identified from the review are sorted in terms of market segments. Table 1 presents the distribution of methods across the different market segments. About two thirds of the researched processes have a special focus (e.g. design for longevity, sustainability, recycling) or are designed for a special product (e.g. textile-based sensors, solar-powered textiles). Two of the researched product development processes are meta-analyses of textile product development in companies.

Table 1. Result of the literature research as a distribution across the market segments.

Market segment	**Quantity**	**Specific focus**	**Specific product**	**General method**	**Meta-analysis**
Apparel	13	4	1	8	0
Technical textiles	12	1	8	2	1
Composites	5	4	0	1	0
Home textiles	2	1	1	0	0
Fibre and yarn	3	1	1	1	0
Without allocation (general textile)	2	1	0	0	1
Sum	**37**	**12**	**11**	**12**	**2**

Five of the eight apparel processes [8-12] focus on the implementation of new products in the company and therefore do not focus on the pattern or functional development of the textile. The other three methods [13-15] are for fashion designs such as the question of sewing height of a jacket pockets. These three methods also do not focus on the pattern of the surface manufacturing process or functional development of the textile. A transformation of subjective decisions into technical design parameters cannot be observed in the models, which shows the need for research in this area.

One [16] of the two general methods for the development of technical textiles considers only the yarn material as changeable. In the other method [17] the yarn material and the finishing process are considered as changeable. Both methods therefore do not focus on pattern of the surface manufacturing process or function development.

A large part of the product-specific methods for the product development of technical textiles is based on VDI 2221. A translation of subjective choices into technical design parameters is not observed among the models, providing research possibility into this domain. The application of the VDI 2221 guideline is not observed in the apparel domain. Apparel design relies on abstract concepts and is based on subjective customer requirements.

2.2 Textile Development (TED) Method

For methods like VDI 2221 the textile surface manufacturing process and also the lapping or pattern of the surface manufacturing process have to be pre-determined. If the lapping or pattern has not yet been determined, elaborate, iteration-rich test series have to be carried out. This procedure is neither sustainable nor resource-saving. For this reason, the Textile Development (TED) Method was developed as a general textile product development method in the dissertations [18] and [19]. The TED-Method consists of six steps (Fig. 3) as explained in detail below.

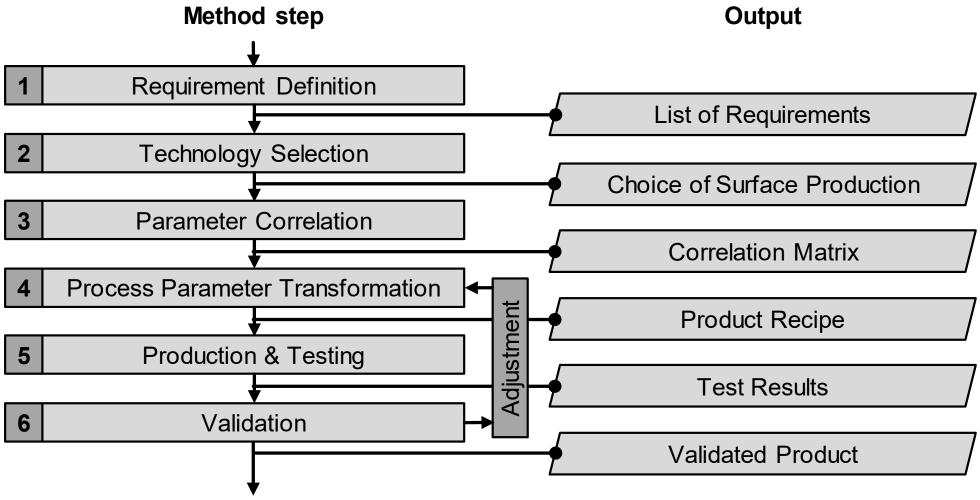

Fig. 3 Overview of the six steps of the TED-Method [20,21].

Step 1 – Requirement definition

Similar to comparable product development methods such as the VDI guideline 2221, the first step of the TED-Method is to determine the requirements for the product to be developed. The requirements to be determined are defined in the TED-Method in five steps (Table 2) [18]:

Table 2. Procedure of requirements definition according to the TED-Method [18].

Step	Name	Result
1-1	Collection of customer requirements and boundary conditions (per area)	List of overall customer requirements
1-2	Consideration of the textile process/machine possibilities and limits	Reduced requirements list
1-3	Linking to test methods	Definition of evaluation framework
1-4	Ranking of requirements	Prioritized list of requirements
1-5	Creation of the final target requirements list	List of requirements with measurable target values

In the first step of requirements definition, all general and partly non-measurable requirements are identified. The requirements are collected, for example, by means of workshops and surveys [19]. Examples of non-measurable requirements are: soft, strong or good climate comfort [21]. In the second step of requirements definition, the list of requirements is reduced by considering the textile possibilities and limitations. If a requirement cannot be changed by the textile process (e.g. lighting conditions), this requirement is deleted. The third step in the requirements definition is to link the requirements with test methods. In the fourth step of requirements definition, the requirements are classified and thus prioritized. Through a pairwise comparison, the collected requirements are transferred into a ranked list [18,19]. In the final step of the requirements definition, the requirements are linked to measurable target values and thus a final target requirements list is created. If no direct target value is available, benchmark tests are carried out on comparative products [19,21]. Properties that cannot be measured directly are determined via several measurable properties or test standards (e.g. breathability via air permeability and density of the textile) [21]. Thus, the result of the requirements definition is a ranked list of target requirements. In the list of target requirements, a corresponding test procedure and a target or comparison value are assigned to each requirement.

Step 2 – Technology selection

The technology selection according to the TED-Method consists of two steps [18]:

1) Technological comparison of the production processes and process chains through a strengths/weaknesses analysis.
2) Economic process comparison through process cost calculation.

The technological comparison is carried out in dependence of the defined requirements in the requirements definition. The technological comparison must take into account that in addition to the various textile surface production processes such as weaving or knitting, the respective process chain is also considered and compared. Table 3 shows an example of a technological comparison.

The technology selection can be further refined by evaluating the evaluation criteria according to the rank of the requirements list. In this way, the different technologies can be compared numerically on the basis of an evaluation sum. The subsequent economic evaluation of the technology comparison is carried out either according to the static investment calculation or the dynamic investment calculation [19].

Table 3. Textile fabric production technology comparison table; - - weak; 0 – neutral; + - strength; ++ - strong strength.

Evaluation criteria (extracted from requirements definition)		weft knitting		warp knitting		woven
		flat	round	flat	spacer	
Product	Abrasion resist	-	-	o	+	++
	Strength	-	-	o	+	++
	Air permeability	++	+	++	o	-
	Mechanical isotropy	-	-	o	+	++
	Defined openings	+	o	+	+	o
	Bending stiffness	-	-	o	++	+
	Continuation of error	-	-	+	++	o
	Form complexity	++	-	+	o	-
Process	Scalable	++	-	+	+	o
	Low no. of yarn guides	++	++	o	o	+
Economic Properties	Production steps	++	+	o	-	-
	Productivity	-	++	+	-	o
	Set-up time	++	++	o	-	-

Step 3 – Parameter correlation

The aim of the third step of the TED-Method, the parameter correlation, is to establish a correlation matrix. The correlation matrix indicates the dependency of the fabric properties selected from the requirement definition with the variables of the selected technology. The variables are, for example, variables of the yarn material, the machine settings or the selected design/pattern. The matrix is established via a literature review and/or a Design of Experiments (DoE) study [21]. Fig. 4 represent general correlation matrices for the surface production methods weft knitting, warp knitting, and weaving. The matrices were determined through both literature research and a DoE study specifically set up for the development of the TED-Method.

round weft knitted fabrics			Machine parameter	Design parameter			
Product properties			No of pile	Yarn tension	Knock over depth	Amount tuck	Amount miss
Strength	Course	[N]	⇈	↑	↑	→	→
	Wale	[N]	⇈	→	↑	→	→
Elongation	Course	[%]	↘	↘	⇊	↗	→
	Wale	[%]	→	↗	↗	→	↑
Air permeability		[mm/s]	↓	↘	↓	↘	↓
Material thickness		[mm]	↗	→	→	↗	↑
Mass per unit area		[g/m²]	⇈	↗	↑	↗	↗

woven fabrics			Machine parameter		Design parameter
Product properties			Warp tension	Weft density	Interlacing
Strength	Warp	[N]	→	↑	↑
	Weft	[N]	→	↑	↑
Elongation	Warp	[%]	↓	↓	↓
	Weft	[%]	→	↓	↓
Air permeability		[mm/s]	↑	↓	↓
Material thickness		[mm]	↓	↑	→
Mass per unit area		[g/m²]	↓	↑	→

closed plain warp knitted fabrics			Machine parameter		Design parameter				
Product properties			Machine gauge	Efective arches per centimeter	Underlay length	Number of guide bars	Inlay (b)	Close lap (b)	Reinforcing fringe (b)
Tensile strength	Course	[N]			↑	↑		↓	
	Wale	[N]			↓	↑	↑	↓	↑
Bending stiffness	Course	[%]	↑		↑	↑		↓	↑
	Wale	[%]		↑	→	↑		↓	↑
Mass per unit area		[g/m²]	↑	↑	→	↑	↓	→	

Fig. 4 Correlations matrixes. Top left: matrix for round weft knitted fabrics [18]; top right: matrix for closed plain warp knitted fabrics [22]; bottom: matrix for woven fabrics; (b): boolean parameter ⇈ - strong increase; ↑ - increase; ↗ - weak increase; → - no influence; ↘ - weak decrease; ↓ - decrease; ⇊ - strong decrease.

Step 4 – Process parameter transformation

The fourth step of the TED-Method, the process parameter transformation, consists of three steps:

1. fuzzification of requirements
2. transformation into machine and design trends
3. abstraction of product recipe

First, the concrete target requirements of the requirements definition are transformed into tendencies via fuzzification. The fuzzification of the target requirements is carried out via the non-measurable requirements description in the first step of the requirements definition. With the help of the correlation matrix, these tendencies of the product characteristics are then transferred into machine and design tendencies. In the last step, a concrete product recipe is abstracted from the machine and design trends and tendencies [18]. The limit values are defined by the selected technology.

Step 5 – Production & testing

In the fifth step of the TED-Method, the developed product is produced according to the process parameter defined in step four. The product is then tested according to the tests defined in step one [21].

Step 6 – Validation (& adjustment)

In the last step of the TED-Method, the results of the test from step 5 are compared with the requirements in step 1. If the product properties do not lie within the range of requirements, steps four to six are repeated with new machine settings [21]. In addition, the product is evaluated in the validation according to technical, economic and ecological aspects [18,19].

3 Results of textile product development following the TED-Method

In this section, three different product developments are presented using the TED-Method. The textile product developments have been carried out in the field of clothing, automotive and technical textiles. The product development examples thus exemplify the diverse application possibilities of the TED-Method.

3.1 Figures

Reference 18 describes the development of a sports shoe upper using the TED-Method (Fig. 5Fig.). In the first step of the TED-Method (requirements definition), the requirements for the new shoe upper are identified. As most important requirements the performance characteristics, lightweight structure and providing areas with different functional zones were defined. To obtain measurable target values, benchmark tests on a weft knitted shoe were carried out [18].

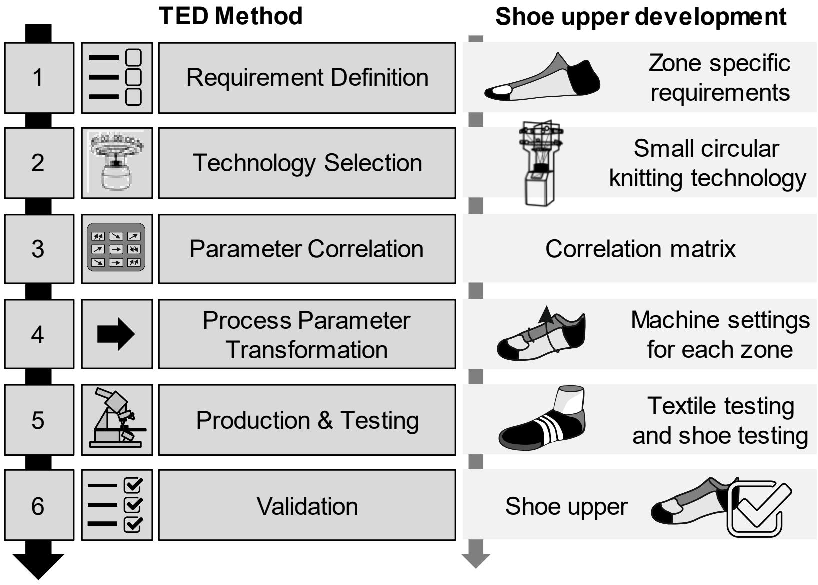

Fig. 5 Product development of a weft knitted shoe upper using the TED-Method [18].

In the second step of the TED-Method (Technology Selection), the three available weft knitting technologies were compared and evaluated regarding their suitability as production technology for shoe uppers. Small circular knitting was chosen as it showed the most suitable behaviour regarding knitting flexibility and economical aspects. In the third and fourth step of the TED-Method (Parameter Correlation & Process Parameter Transformation), the weft knit correlation matrix was used to identify machine input values for each zone of the shoe uppers. Based on this, in the fifth step of the TED-Method (Production & Testing) a prototype was produced and tested. Following the requirements list, the shoe prototype has been tested regarding the fulfilment of the defined requirements. The validation in the sixth step of the TED-Method demonstrates that the main requirements for each zone have been fulfilled. The shoe possesses a high elastic zone for the step-in comfort. For heel and toe, a cushioning zone has been realized. Additionally, a highly breathable zone has been integrated to improve the air circulation properties [18]. In a subsequent validation process, the shoe upper was then equipped with a sole and the complete shoe was tested. Shoe stability as well as fit and feel were tested. Overall, the shoe prototype has been rated with 7.5 out of 10 points (very good) [18].

Through the TED-Method, the rather unconventional manufacturing technology of small circular knitting was chosen for the shoe upper. The desired mechanical properties could all be fulfilled. Simultaneously the production process is nearly eight times faster compared to the flat knitting technology. Overall, the development process of a knitted shoe upper improved due the applicability of the TED-Method. With the help of the correlation matrix, the number of iteration steps was reduced to zero and a competitive shoe upper was developed within the first iteration cycle. Compared to the conventionally used trial and error method, the TED-Method helped to reduce time as well as cost and unnecessary material waste due to several iteration steps in the development process [18].

3.2 Application example automotive – seat cover and head liner

Reference 19 describes the development of recyclable seat covers and head liner using the TED-Method (Fig. 6). In the first step of the TED-Method (Requirement Definition), OEM (Original Equipment Manufacturer) specifications have been collected to analyse the necessary requirements for the final products. To conclude the target values, benchmark tests have been carried out. In the second step of the TED-Method (Technology Selection) weft knitting spacer technology has been chosen for both products. Weft knitted spacer fabrics possess slightly higher production costs than conventional fabrics. Due to the water vapour transmission resistance and the breathability of weft knitted spacer fabrics this technology was chosen in the technology selection. The weft knit correlation matrix was extended to spacer weft knits in the third step of the TED-Method (Parameter Correlation) using a DoE-study. From the correlation matrix and the list of requirements, suitable machine settings have been defined in the fourth step of the TED-Method (Process Parameter Transformation). In the fifth step of the TED-Method (Production & Testing), a prototype was produced for each of the products and tested according to their list of requirements. The resulting fabrics have been analysed in accordance with the requirements list regarding conventional textile tests and automotive specific textile tests. In validation, the sixth step of the TED-Method, the test results are compared with the requirements. The test results showed that the spacer fabric fulfils all requirements. Both, the seat cover fabric and the head liner fabric, showed good climate comfort properties regarding water vapour and heat transmission resistance. The fabrics can be used as a passive climate fabric and therefore generated the desired benefit for the customer. Moreover, the fabric consists of only PES (Polyester) yarn instead of a combination of PES fabric and PU (polyurethane) foam. Therefore, the aim to produce a recyclable textile to substitute the foam is also fulfilled. Overall, the technical, economical and ecological aspects are achieved by the new developed textiles [19].

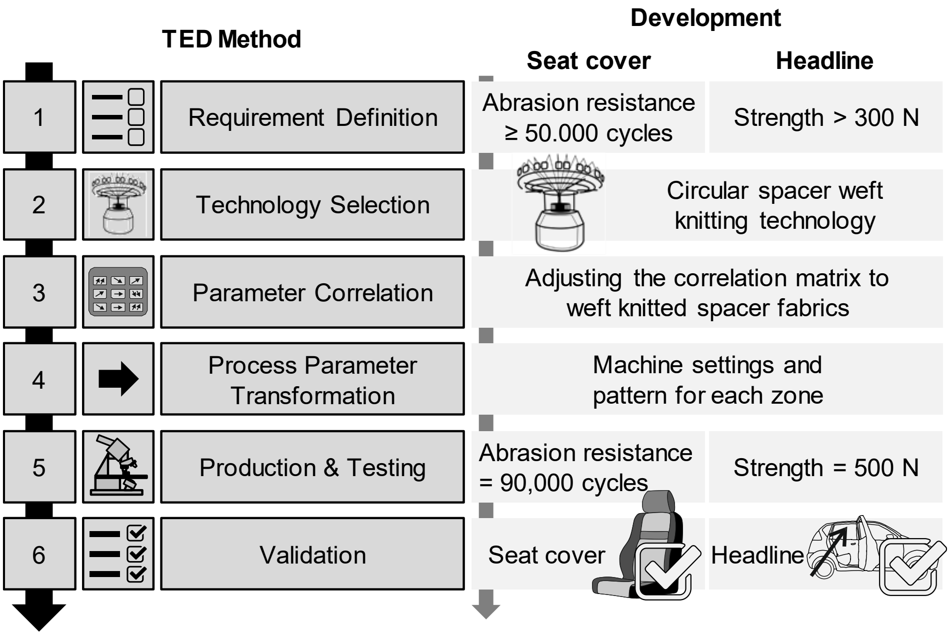

Fig. 6: Product development of a spacer weft knitted seat covers and head liners using the TED-Method [19]

In summary, through the application of the TED-Method, the product development of the seat covers and head liners was much faster without unnecessary iteration steps. The developed textiles possess comparable mechanical properties to the conventional textiles and show additional benefits regarding climate comfort and recyclability. These aspects represent a distinct improvement compared to the state-of-the-art. Through the use of the correlation matrix the number of iteration steps for the development was reduced to zero [19].

3.3 Application example technical textiles – textile reflector surface

In Reference 20, the development of a textile reflector surface for satellites using the TED-Method is described (Fig. 7). Reflectors for large deployable reflector antennas (LDA) are part of satellites that are usually used on in-orbit missions for telecommunication service. The reflectors of LDAs are up to 20 m in diameter and thus folded for the in-orbit transport. The reflecting surface, the reflector surface, is usually made out of a textile, mainly metal warp knit or carbon fibres reinforced silicon (CFRS) weave [23]. The newly developed reflector surface aims to offer the advantages of current mesh reflector surfaces (lightweight and foldable) as well as the ability to reflect frequencies in higher frequency bands such as the Ka-band (27-40 GHz). To achieve this, the surface must be stiffer and form a closer structure than current mesh reflector surfaces [20,24].

In the first step of the TED-Method (Requirement Definition), all requirements are defined and prioritised. The collected requirements are divided into requirements for the yarn material and the textile structure. The yarn requirements in particular are determined by the specific location of the geostationary location of the later reflector surface [24]. The particular challenge in the development of textile reflector surfaces for LDAs is the yarn material to be used. The yarn material must be able to reflect radio frequency waves as well as withstand the special temperature properties of the geostationary orbit (from -190 °C to +140 °C in a 24 h cycle). Only fine metallic wires meet these requirements [25, 26]. In the second step of the TED-Method (Technology Selection), through a technological comparison, a decision is made in favour of warp knitted spacer fabrics as the textile structure and fine molybdenum wire as the yarn material. The existing correlation matrix for warp knitted fabrics is extended to warp knitted spacer fabrics in the third step of the TED-Method (Parameter Correlation) through a DoE study and a literature research. In addition, the correlation matrix is extended to the special product properties of the requirement list. From the comparison of the established correlation matrix with the list of requirements, a suitable pattern for the reflector surface is chosen in the fourth step of the TED-Method (Process Parameter Transformation). In the fifth step of the TED-Method (Production & Testing), production and subsequent testing of the chosen pattern is carried out. By comparing with the list of requirements in the sixth step of the TED-Method (Validation), it is determined that the validation of the product in this application example is not successful. For this reason, steps 4 to 6 of the TED-Method are repeated and an adaptation of the textile structure is carried out. The new structure consists of a glass fibre back side and pile-layer with a functional molybdenum front side. The adapted structure is successfully validated and is currently being further developed for the next TRL (Technology Readiness Level) of this structure [20,27].

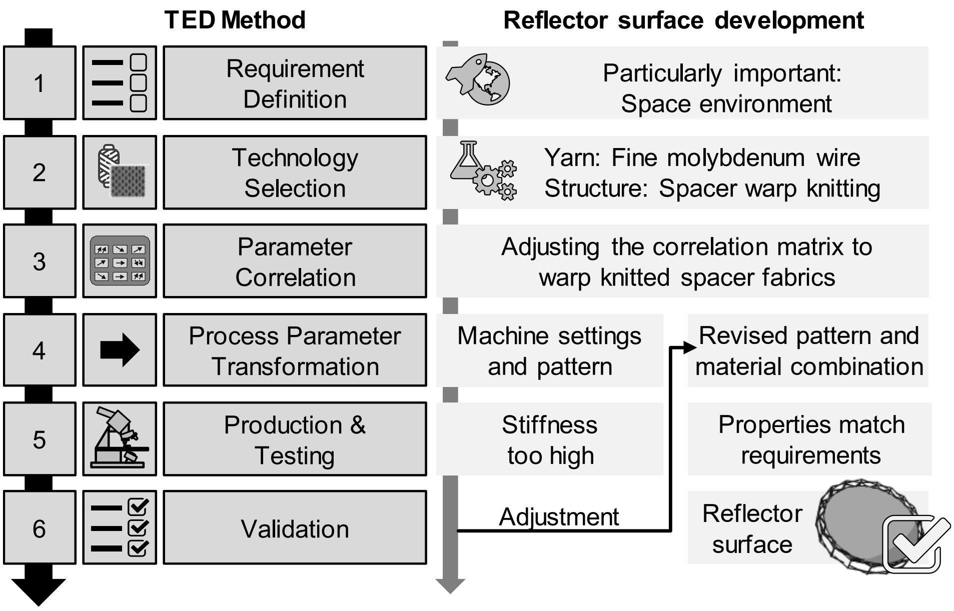

Fig. 7 Product development of a spacer warp knitted reflector surface using the TED-Method [22]

4 Conclusion

In summary, this paper presents a new method to develop new textile products in a structured and cost-saving way. The presented TED-Method closes a necessary methodology gap for the development of textile products where the manufacturing process and the pattern are not yet predetermined. The TED-Method impresses with its iteration-free development without trial and error trials in two of the three application examples. In the third application example, only one iteration was needed to create a successful product. Elaborate, iteration-rich test series have not been carried out. It is shown, that the TED-Method is a sustainable and resource-saving alternative to traditional textile product development.

Author Contributions

I. Bettermann: conceptualization, methodology, formal analysis, writing – original draft preparation, writing – review and editing; D. Mukherjee-Kleiber: data curation, writing – original draft preparation; R. Heesemann: data curation, validation, writing – review and editing; T. Gries: supervision. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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