RIGA TECHNICAL UNIVERSITY

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IMPROVEMENT OF SMART TEXTILE PRODUCTS DESIGN

Summary of doctoral thesis

Riga 2014

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Faculty of Material Science and Applied Chemistry

Institute of Design Technologies

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„Clothing and Textile technology”

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DOCTORAL THESIS HAS BEEN PROMOTED FOR OBTAINING DOCTOR'S DEGREE IN ENGINEERING SCIENCES (MATERIAL SCIENCE, TEXTILE AND CLOTHING TECHNOLOGIES) IN RIGA TECHNICAL UNIVERSITY

The defense of the doctoral thesis for scientific degree of Doctor of Science in Engineering will take place at an open session on April 25, 2014, at 12:00, at Riga Technical University, Institute of Design Technologies, Āzenes 18, room 117, Riga, Latvia.

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CONFIRMATION

Hereby I confirm that I have worked out the present doctoral thesis, which is submitted for consideration at Riga Technical University for achieving scientific degree of Doctor of Science in Engineering. This doctoral thesis is not submitted to any other university for achieving scientific degree.

Inese Parkova …………………………….(Signature)

Date: ………………………

The doctoral thesis is written in Latvian. The doctoral thesis consists of 4 chapters. The references include 147 sources. There are 106 figures, 77 formulas and 24 tables to illustrate the conception of the carried out research. The doctoral thesis contains 172 pages.

Content

INTRODUCTION

The purpose of a smart textile product is to improve the properties of traditional clothing/textiles and complete them with new functional properties. There are different types of smart textile products; however, this dissertation considers only the textile products with integrated electronics.

Electronic systems and devices integrated in smart textile products can perform different functions in such areas as health supervision, communication, energy storage, active or passive thermal conductivity, protection, entertainment, etc. From the point of view of healthcare development, sensors and communication devices can be integrated in clothes or accessories in order to monitor, report about and improve patients' health and comfort. Circuits integrated in textiles can also be used for sports clothes and functional textile products. They can establish contact with mobile phones, computers, interactive jackets, bags, textile keyboards, etc. [107].

Topicality of the dissertation:

Electronically equipped items are often hard, non-elastic and therefore not comfortable to use because they contain rigid wires, massive batteries, large electronic units, etc. Clothing become a platform for an electronic system and in most cases is uncomfortable to wear. One of the purposes of improving smart textiles and smart clothing is to work an electronic system right into the fabric structure without making substantial changes to the visual and physical properties of the material [149].

This area is still new and developing, and therefore the existing clothing solutions with integrated electronics are difficult to maintain and should be used with extreme care. The efficiency of performing technological functions at a high level is an important aspect of smart clothing; however, if the clothing is uncomfortable, it will not be used. The given topic is very essential, and practical research is being made in several directions of this sphere the development of which can bring both social and scientific success.

Aim of the dissertation:

- To improve the process of designing smart textile products for the enhancement and more precise forecasting of their performance characteristics.

Objectives of the dissertation:

- To study the types of smart textile products, design of electronic systems and technology of integrating them in textile products;
- To analyze the types of materials for smart textile products and the technologies of their processing;
- To set the requirements for designing smart textile products in order to make safe and comfortable products;
- To study the properties of conductive textile materials and the changes they undergo under the influence of various conditions and factors;
- To develop prototype models for separate smart clothing / smart textile designs – fibre technology, integration technology and block technology; to check the durability of samples, safety and efficiency of the system operation by using the methods and techniques of electronic system integration;
- To adapt the decision making method to the evaluation and comparison of smart textile product systems.
- To develop a structural diagram of the process of smart textile product design on the basis of theoretical material analysis and experimental research work.

Methodology and research methods:

- Analysis of scientific literature and assessment of practical experience, systematization, consolidation of results in flow charts and tables;
- Algorithmization theory, systemic analysis of complex object structure;
- Planning of multi-factor experiments to study the electrical properties of yarns, strength of interconnections and speed of a moisture sensor;
- Registration of measurements to characterize the electrical properties of electronic systems – a digital multimeter for measuring electrical resistance, an environment meter for measuring the emitted light, an oscilloscope for measuring electric voltage.
- Use of statistical analysis – graphic analysis of data, descriptive statistics, pair correlation;
- Application of decision making methods for the description of experimental data and creation of algorithms – *Electre I, Analytic Hierarchy Process (AHP);*
- Application of C programming language for the creation of prototype models – a textile display, a moisture sensor, a microclimate monitoring jacket;
- Use of *PicoScope 6* software for recording electric voltage data;
- Use of computer graphic and computer simulation programs for designing the prototype models – *Adobe Photoshop, Adobe Illustrator, PC-Edit, WeavePoint, PE-Design*.

Scientific novelty of the dissertation:

- A structural diagram of smart textile product design works has been developed by laying emphasis on textile, electrical engineering and electrotextile technologies and characterizing their interaction from the point of view of choosing a relevant design solutions for smart textile products;
- Factors (seam parameters, type of circuit insulation and operating conditions) affecting the electrical properties of smart textile product system interconnections have been determined for a more precise forecasting of the system behavior and making a suitable choice of materials;
- New woven electroactive textile structures and a new technology for integrating electronics in textiles and designing interconnection components have been developed;
- Restrictions for locating electronic systems have been identified and system configuration assessment criteria for smart clothing have been selected. *ELECTRE* decision making method for optimizing the location of smart closing system components has been adopted.

Practical relevance of the dissertation:

- Criteria for choosing conductive textile materials and integration technologies to be considered when designing a textile circuit have been developed;
- Information about the types of materials and technologies for designing textile products equipped with an electronic system have been compiled and systematized;
- A structural diagram for designing smart textile products and recommendations for its practical use have been created;
- A textile moisture sensor for nocturnal enuresis alarm has been developed and tested, the wearing comfort of therapeutic clothing has been enhanced;
- A woven textile display has been developed; it has a special network that make it possible to isolate vertical and horizontal conductive contacts and integrate an electronic device in a textile structure without deforming the fabric structure;
- A woven textile display with a weave that allows to vary the intensity of emitted light by the fabric structure has been developed.

Patents:

- The practical importance of thesis is confirmed by the patent - Latvian patent No. 14680 “Elastīgs gaismu izstarojošs tekstila displejs ar pārstaipiem elektronikas ierīču nosegšanai” (issued 2013th on 23rd March);
- Filed in the European patent application EP13193532.2 “Flexible light-emitting textile display with floats for covering electronic devices” (submitted 2013th on the 19th November).

Approbation of the dissertation

The main results of the doctoral thesis have been presented at 13 scientific conferences with 16 reports:

1. ICMIME 2014 : International Conference on Manufacturing, Industrial and Materials Engineering. Lisbon, Portugal: April 17th - 18th, 2014
2. The 22nd International Baltic Conference of Engineering Materials & Tribology – BALTMATTRIB 2013. Riga, Latvia, November 14th–15th, 2013
3. RTU 54. starptautiskā zinātniskā konference. RTU, Riga, Latvia: October 11th, 2013.
4. 6th International Conference on Computational Methods and Experiments in Materials Characterisation. Siena, Italy: June 4th – 6th, 2013
5. 4th International Conference of Smart Materials, Structures and Systems. Montecatini Terme, Italy: 10th -14th June, 2012
6. RTU 53. starptautiskā zinātniskā konference un 1. pasaules inženieru un RPI/RTU absolventu kongress. Riga, Latvia: October 10th-12th, 2012.
7. 14-th Romanian Textiles and Leather Conference - CORTEP'2012. Sinaia, Romania: September 6th-8th, 2012.
8. Apvienotais Pasaules latviešu zinātnieku III kongress un Letonikas IV kongress „Zinātne, sabiedrība un nacionālā identitāte”. RTU, Rīgā: 2011. g. 25. oktobris
9. RTU 52. starptautiskā zinātniskā konference. RTU, Riga, Latvia: October 12th, 2011.
10. 8th International Scientific and Practical Conference “Environment. Technology. Resources.” Rezekne Higher Education Institution, Rezekne, Latvija: June 20th – 22th, 2011.
11. RTU 51. Starptautiskā zinātniskā konference. RTU, Riga, Latvia: October 11th – 15th, 2010.
12. RTU 51. studentu zinātniskā un tehniskā konference. RTU, Riga, Latvia: April 16th, 2010
13. 9th International Conference on Global Research and Education Inter-Academia 2010. RTU, Riga, Latvia: August 9th – 12th, 2010.

The author of the doctoral thesis is the author and co-author of 20 scientific research publications. 6 of these publications are included in recognized databases (Scopus, ISI Web of Knowledge, SciFinder, Ebsco. The research results of the thesis are presented in international conference proceedings, scientific journals and other recognized by Latvian Council of Science scientific journals.

1. **Parkova, I.,** Vališevskis, A., Viļumsone, A. Test of Moisture Sensor Activation Speed. In: Proceedings of ICMIME 2014: International Conference on Manufacturing, Industrial and Materials Engineering, Lisbon, Portugal, April 17th-18th, 2014. World Academy of Science, Engineering and Technology, pp. 1-5. Accepted for publication.
2. **Parkova, I**. Woven Textile Moisture Sensor for Enuresis Alarm Treatment. Key Engineering Materials, 2014, Vol. 604, pp 146.-149. ISSN 1662-9795.
3. **Parkova, I**., Viļumsone, A. Insulation of Flexible Light Emitting Display for Smart Clothing. In: Proceedings of International Conference on High Performance and

Optimum Design of Structures and Materials: 6th International Conference on Computational Methods and Experiments in Materials Characterisation, Siena, Italy, June 4th-6th, 2013. Southampton: Wessex Institute of Technology, 2014, pp 1.-12. Accepted for publication.

4. **Parkova, I**., Viļumsone, A. Functional and Aesthetic Design of Woven Electrotextile. Journal of Textile and Apparel, Technology and Management, 2013, Vol.8, No.2 , pp 1.-9. ISSN 1533-0915. *Indexed Scopus and Ebsco host connection*.
5. **Parkova, I**., Vališevskis, A., Užāns, A., Viļumsone, A. Analysis and Improvement of Nocturnal Enuresis Alarm System. Industria Textila Magazine, 2013, Vol. 64., No.6, pp 355.-361. ISSN 1222-5347. *Indexed Scopus*.
6. **Parkova, I**., Parkovs, I., Viļumsone, A. Light-Emitting Textile Display with Floats for Electronics Covering. International Journal of Clothing Science and Technology, 2013, Vol., pp 1.-20. ISSN 0955-6222. Accepted for publication.
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ABSTRACT

The doctoral thesis „Improvement of smart textile products design" has been worked out by Inese Parkova to get the scientific degree of Doctor of Science in Engineering. Scientific supervisor of the work is Dr.sc.ing., professor Ausma Vilumsone, consultant – Dr.sc.ing., lead researcher Aleksandrs Vališevskis.

The aim of dissertation is to improve the process of designing smart textile products for the enhancement and more precise forecasting of their performance characteristics based on analysis of different types of electronic systems embedding technologies as well as clothing and textile adaption technologies.

In introduction part research topicality is outlined, research goal and objectives are defined, research approbation is stated.

In the first chapter review of smart textile products is performed, electronic elements for smart textile products design are described and electrotextile designing technologies are illustrated.

In the second chapter research used materials and methods are described (data analyze methods, test methods, measurement methods).

In the third chapter results are presented. Properties of electro-conductive textile materials and its changes was studied as well as three prototype groups were designed and analyzed, which describes different ways of electronic system attachment to smart textile products – moisture sensor (fiber technology), textile displays (integration technology), microclimate monitoring jacket (block technology).

In the fourth chapter structure of initial data for smart textile products design was formed and structural model of smart products design process was developed, which displays criteria of materials and technologies selection and links of design process stages.

In the last chapter conclusions of the research are discussed.

Doctoral thesis includes introduction, 4 chapters, conclusions, list of literature with 147 sources, 4 appendices, 106 figures, 24 tables. Thesis contains 172 pages.

1. THEORETICAL BASIS OF SMART TEXTILE PRODUCTS DESIGN

In literature are used different terms of textiles and clothing with embedded electronics. In standard [117] is defined that functional textile material is textile material to which a specific function is added by means of material, composition, construction and/or finishing (applying additives, etc.). It can be electricity, light or heat conductive textile materials, fluorescent or phosphorescent textile materials etc. In its turn smart textile material is functional textile material, which interacts actively with its environment, i.e. it responds or adapts to changes in the environment. It can be chromic, phase change, shape change (shape memory), piezoelectric, electroluminescent, photovoltaic, capacitive textile materials etc. Smart textile system consists of sensors, actuators and information management devices. The information within the smart textile system can be controlled and/or managed by electronic device(s) (such as a processor). Such textile systems are also called e-textiles (electronic or electroactive textiles) or textronics. Smart clothing is obtained by integrating functional or/and smart textile materials into clothing.

To systematize information about types of smart textiles products they were described by three criteria: working types of system, technological constructions and the basic elements (functions). Electronic components what can be used for smart textile products design were described and classified in order to help to define specialization of element and to choose the most suitable element for a specific product. Electrically conductive textile materials were discussed and classified as well as current electrotextiles design technologies were illustrated. Each technology has its own advantages and disadvantages depending on the type of application.

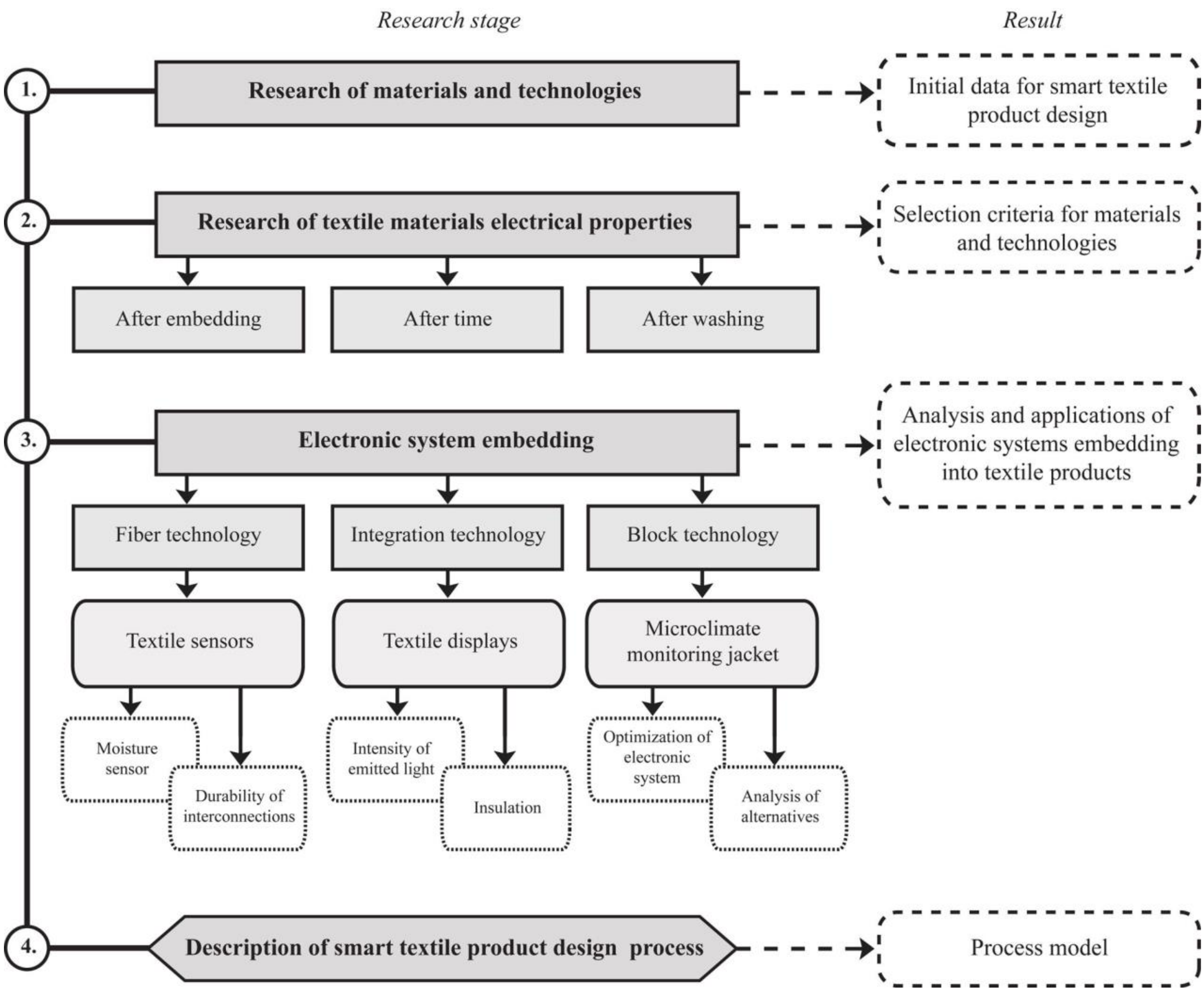
During the last decade the development of electrotextiles has progressed, but still there are things which should be developed and improved. For example, the research issues such as yarn topology and structural deformation of fabrics-based sensors have not been fully explored yet [51]. Although the conductive yarns and fabrics have been studied in various products (for example, in textile interfaces), there are not available a study which describes in detail electrical behavior of conductive yarns and textile and its influencing factors [132]. Therefore, it is necessary to study the integration of conductive yarns into textile structure by analyzing yarns’s electrical conductivity under the influence of various variable factors and actions.

Definition of electroactive textiles application is important as well. Since electroactive textiles are still under development, it is necessary to enlarge the range of its assortment designing products with new features and for different applications.

The objective of smart clothing is to fulfill a specific function, facilitating or improving human living conditions. To avoid reducing of clothing quality and wear comfort, clothing with embedded electronic system should both safe and comfortable. Wearing comfort is one of the most important factors that encourage users to accept and wear this type of clothing. To improve this condition, smart clothing system must comply with the characteristics of textile products, as well as it should take other factors affecting the comfort of garment wearing. Thus, in theoretical part the factors influencing the wear comfort are analyzed as well.

2. MATERIALS AND METHODS OF EXPERIMENTS

In promotional work electrical properties of textile materials and its changes were studied, as well as three prototype groups were designed and analyzed in order to characterize different types and technologies of electronic system embedding into textile products – moisture sensor (fiber technology), textile displays (integration technology) and microclimate monitoring jacket (block technology). Research structure in stages is shown in Fig. 2.1.



2.1. att. Structure of research experiments

Characteristics of conductive yarns which were used in experiments are summarized in Table 2.1. For design of functional textile samples different technologies were used - weaving, sewing and embroidery. Since this study is focused on the development of technological process, in promotional work manufacturing process of samples is described in detail, which could promote understanding about electroactive textile design specific characters.

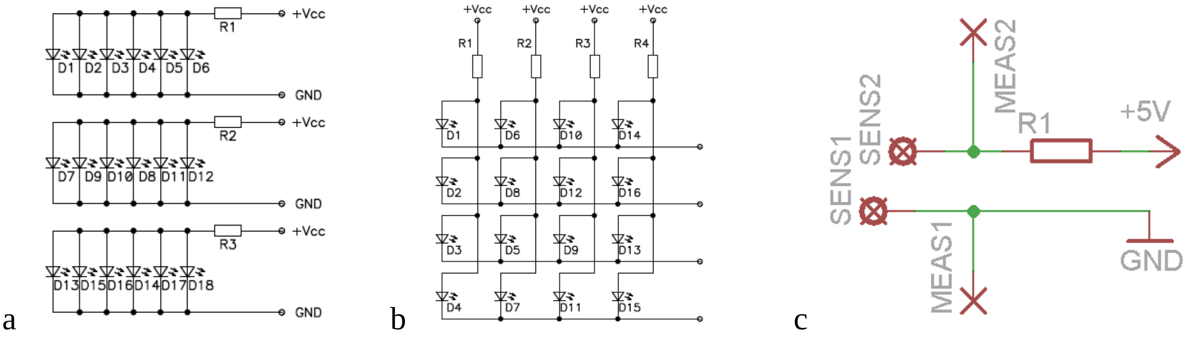
On the basis of theoretical and experimental experience smart textile product design process model was developed.

Table 2.1.

Characteristics of conductive yarns

Code	Name	Linear density, dtex	Structure and composition
N1	Elitex	110/34	Single ply, polyamide, silver coated
N2	Elitex	110/34 x2	2 ply, polyamide, silver coated
N3	Shieldex	235/34 x4	4 ply, polyamide, silver coated
N4	Shieldex	110/34 x2	2 ply, polyamide, silver coated
N5	Karl Grimm	330/34 x7	7 ply, polyamide and copper fibers

In electroactive textile samples parallel port circuitry (LED display II), matrix circuitry (LED display I and III) and two-electrode scheme (humidity sensor) were used. The circuits are shown in Fig. 2.2.



2.2. att. Circuits of electroactive textile samples – a: parallel port circuitry; b: matrix circuitry; c: two-electrode scheme

Test methods of samples:

- Stability of electrical conductivity during light and time. Periodical measurements of electrical resistance were performed during 5 months (from December to April), samples were indoors with an average air temperature of 19 ° C.
- Stability of electrical conductivity during washing. Washing is the most common test for smart textiles. Washing tests were performed according to standard ISO 6330:2012 *Textiles - Domestic washing and drying procedures for textile testing*.
- Resistance to abrasion. In insulation experiment *The Taber Rotary Platform Abraser* was used in order to evaluate resistance to abrasion of coating and electrical components. Test abrasive wheel: H18, load: 250 g, speed: 60 cycles / min.

Measurement methods of samples:

- Electrical resistance and conductivity. For measurements of electrical resistance digital two probes multimeter was used. The electrical resistance of conductive yarns was measured in a continuous form (seams test, humidity sensor) or compound form (humidity sensor). The electrical resistance was measured before and after tests (washing) and depending on the number of characters (yarn type, seam length, number of parallel seams, number of package layers, integration technology) or under the influence of various variable factors and actions (changes over time, changes under load, change after washing).

- Light intensity. Emitted light in electrotextiles was measured with a digital environment meter *Velleman DVM401* using luxameter function. Measurements were taken in a dark room.
- Moisture sensor activation speed. In the experiment 0,2 moles of salt per 1 liter of water solution was used, because its conductivity corresponds to the average conductivity of urine [9]. Solution was dripped (4 drops) from drip funnel on sensor, while holding funnel at 5 cm distance from horizontal surface of sensor. Measurements of electrical signals were performed with a digital oscilloscope and data was captured using *PicoScope 6* software. With the oscilloscope change of voltage (U) after liquid dripping was determined.

3. SUMMARY OF RESEARCH RESULTS

Although inspiring results have been reported in the past, problems such as complicated process, washability and comfort are still under investigation. In order to improve wearable electronics features, system connections should be high quality and reliable conductors of electricity and they should ensure traditional garment comfort, i.e. they should be resistant to friction, bending, cleaning, as well as other types of processing. Besides that smart garments should keep outstanding hygienic and bending properties. It is rather difficult to combine all these properties due to the different nature of electronic and textile components.

3.1. Analysis of smart garment electronic contact system

During previous research designing smart garment prototype [95], most of the problems were caused by the connection points of electronic components, which were made with conductive yarns using a sewing machine. Therefore this study focuses on the analysis of behaviour of conductive yarns and improvement of the connection points. During research integration of conductive yarns into textile structure has been studied, analyzing conductivity of yarns before and after they have been sewn into fabric. Variable factors of the experiment were: yarn type, stitch length, number of parallel seams, number of package layers, type of integration. Seams durability tests have been performed, which enabled to measure changes in electrical resistance in the long-term (during 5 month period) and changes in electrical resistance after washing. In the result of the study recommendations and selection criteria for electrically conductive textile materials and technologies were developed, what should be taken into consideration during design of textile circuits:

- Structure of conductive yarn

  Multi-ply conductive yarns are more durable and suitable for sewing/embroidery, they produce better quality seams than single ply yarn does, which breaks and makes fuzzes during sewing. Multi-ply conductive yarns are more stable after washing as well. After wash test electrical resistance of multi-ply yarns increased less: after third was cycle increase of resistance for multi ply yarns was in average 92% and for single ply yarns - in average 336%.
- Sewing process.

  If conductivity of a yarn has an impact on tension, its behavior can be affected by sewing process – type of machine, tension of yarn, length of stitch.
- Placement in garment

  It is not preferable to place conductive yarns in tension subjected areas on garment, which can lead to short-term change of resistance or breakage of yarns.
- Change of electrical properties under the influence of environmental factors

  Usage of embroidery or sewing for circuit designing conforms to keeping comfort in textile garment, but from point of view of electronics these connections are not very reliable. Instability of connections made with conductive yarns can lead to unexpected problems in electronic circuitry. Thus, when choosing a particular yarn, it is important to study how its conductivity changes over time both due to contact with atmospheric moisture and due to mechanic abrasion, as well as due to washing of the product. These characteristics can vary significantly among yarns, for example, in three washing cycles from 35% to 622%. It is important to note that even for one yarn type influence of washing can depend on the stitch step length. Variation can be as big as 404% (N1, when comparing 1mm and 4mm stitch) or as small as 23% (N3, when comparing 1mm and 2mm stitch).
- Application of electrical circuit

During the design of electronic circuitry it is necessary to take into consideration the changing nature of the conductive yarns and to use appropriate yarns in appropriate places. The main factors are the criticality and sensitivity of the circuit, as well as peak current consumption. One can use Ohm's law to determine the maximum overall resistance of the interconnections given the peak current consumption and the supply voltage. E.g. if you have a 3V power source, two LEDs with optimum performance at 20mA and a transceiver, which peaks at 45mA, then you do not want the overall resistance of interconnections and eventual current limiting resistors to raise above 3V/85mA=35.3 Ω. The allowable fluctuation of electrical conductivity in circuit depends on the type of application. As noted before, conductive yarns with moderate resistance can be used as part of circuitry, e.g. instead of current limiting resistors for LEDs. But it's not rational to use a yarn with 600% change in resistance over a few washing cycles, as the current can become too weak to turn on the diode. Such unstable yarns with high resistance can be used in two-state sensors (pressure, moisture etc.), where it is necessary to differentiate just between the high and the low state. Other applications include non-critical digital communication lines. That said it is important to note that connection with unstable resistance must be absolutely avoided to connect analogue sensors, especially resistive ones, as even slight changes in resistance may introduce a significant measurement error. Digital sensors should be preferred in such systems.

3.2. Design of electroactive textiles

Samples of functional textile (textile sensors and photonic textile displays) were designed and possibilities of weaving technologies in textile circuit design were analyzed.

Textile sensors and durability of its interconnections

In order to make smart clothing more comfortable in use and more conformable to textile materials properties, some part of sensors can be replaced with textile sensors. In thesis design process of pressure and moisture sensors are described, which represents a simple example of fiber technology as one of the type of electronics systems embedding into textile (see Fig.2.1.).

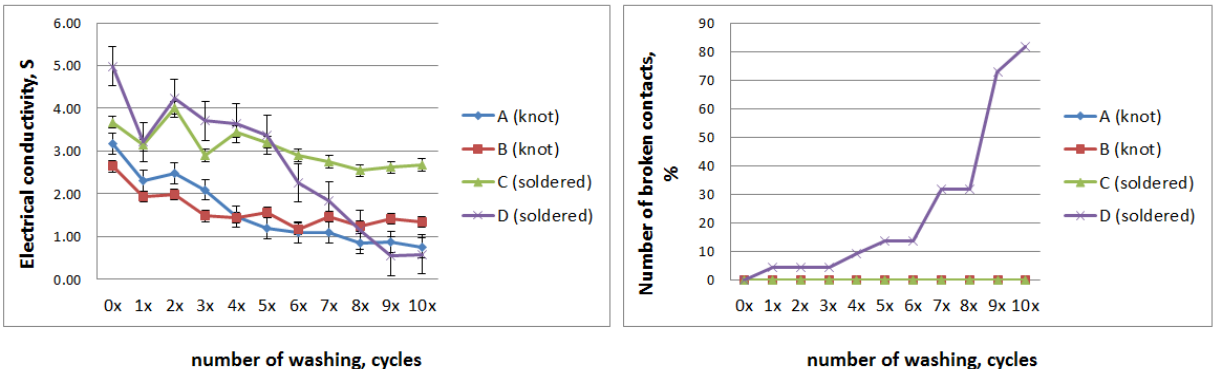
During research several types of interconnections and its durability was analyzed using textile moisture sensor samples. Description of samples is shown in Table 3.1. Interconnection type of electrical conductors can significantly affect quality of electronic system and data management accuracy.

Table 3.1.

Description of samples for interconnections analysis

Sample code	Conductive yarns embedding into textile	Interconnection of electrode's vertical and horizontal contacts
A	Woven / sewn	Knot
B	Woven	Knot
C	Woven	Soldering
D	Woven / sewn	Soldering

Contact tightness was evaluated with conductivity (in Siemens) between vertical and horizontal contacts of electrodes before washing and after each wash cycle. Results are presented in Fig. 3.1. Durability of interconnections depends from both interconnection type and conductive yarn integration type into textile. Washing affects electrical contact durability well.



a b

3.1. att. Electrical conductivity after washing (a) and number of broken contacts after washing, % (b)

Soldered connection provides good and stable electrical contact, however in textile embedded system it is subject to mechanical deformations and in result it can lead to contact breakage. In its turn electrical conductivity in knot connection decreases gradually as the knot becomes loosen over time. After wash test it was concluded that woven structure of electrotextile improves durability of both soldered and knot conductive yarns connections, because contact areas of electrically conductive yarn are partially covered with textile yarns. In woven structure also enhances better sensorial feeling in textile.

Moisture sensor design and its activation speed test

While designing moisture sensor on textile substrate, its wettability and moisture management are especially important. They have direct impact on speed of sensor signal detection – how fast drops of liquid will be absorbed and will spread through fabric surface, forming contact between the two electrodes. When a sensor is integrated into underwear, it is placed close to wearer’s body, therefore in order to keep appropriate hygienic and comfort requirements of clothing wear, it is necessary to ensure as small as possible contact surface between electrical conductors (conductive yarns) and wearer’s body. However at the same time system’s signal detection speed, i.e. time needed for liquid to reach electrically conductive yarns is important as well.

For sensor design experiment sewn, embroidered and woven sensor samples were developed. In the first samples different shapes of electrodes, conductive yarns and distance between conductive seams were used. Samples are described in Table 3.2.

Table 3.2.

Descriptions of samples for moisture sensor design experiment

Type of integration technology	Embroidered	Sewn	Woven
Base material	Cotton fabric	Cotton fabric	Cotton yarns
Conductive yarn	N2, N3, N4	N5	N5
Shape of electrode	A: spiral B: comb-like	B: comb-like	B: comb-like
Distance between parallel seams, mm	0 2	-	-

From tested conductive yarns the best electrical conductivity has copper yarn (N5, electrical resistance 0.2 - 1.9 Ω / electrode) and therefore it was used for subsequent samples. Significant differences between spiral and comb-type configurations weren't observed, whereas with available equipment it is not possible to design woven samples in spiral configuration, for the next samples combs configuration was used.

In this study washed and unwashed woven and sewn samples were tested from the both sides of the sensor and change of electrical voltage after solution dripping on samples was analyzed. Sewn and woven sensor samples have different moisture detection speed. Sewn sensor had better results in system activation test, moisture detection speed was faster – testing sensor from left (top) side signal was activated after 8.7 seconds, from right (bottom) side of sensor – it was activated after 12.5 seconds. In its turn in woven samples testing samples from right side signal was activated after 15 seconds, from left side – after 17.7 seconds. Performance of sensor signal under realistic conditions would be much faster. This test method (dripping 4 drops) was performed in order to compare by objective considerations different structures of moisture sensor samples.

Sensor system circuit was designed and two sensor tests were performed: system activation test and false alarm test to determine the sensitivity of the system and activation threshold. Results are shown in Fig.3.2. and Fig.3.3.

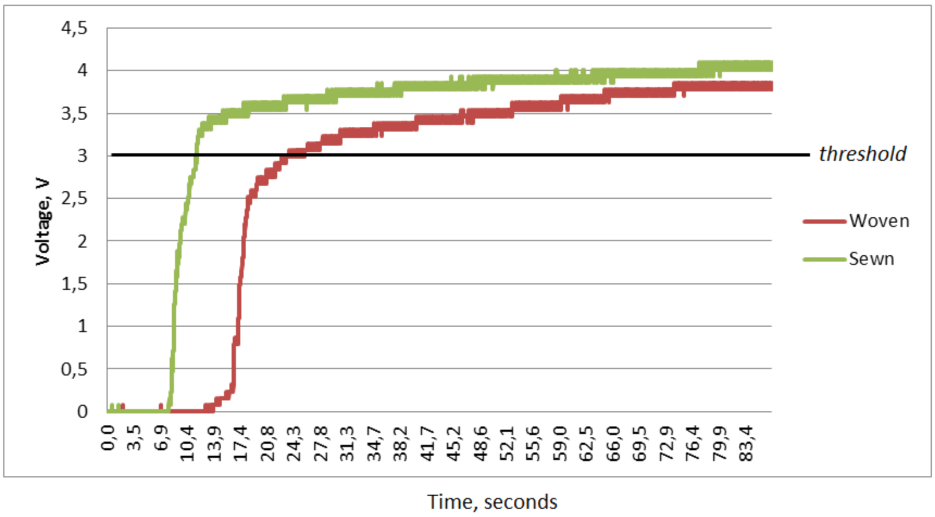


Fig. 3.2. Results of system activation test

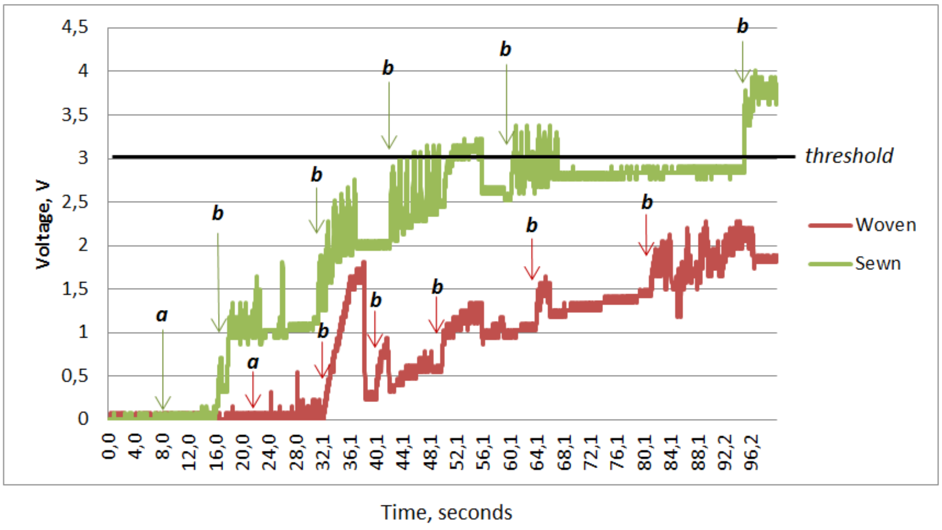
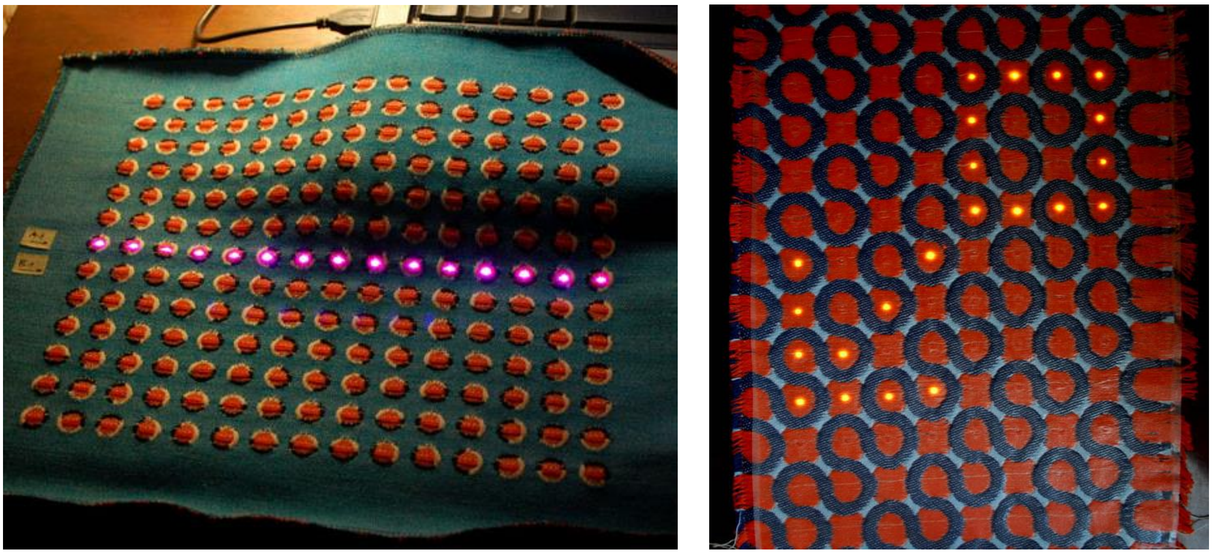


Fig. 3.3. Results of false alarm test– a: change of voltage during rubbing; b: change of voltage during pressing

False alarm test was performed to determine reaction of sensors during sweating. Sweating conditions were simulated by touching surface of sensors with wet cotton fabric. In diagram (Fig.3.3.) change of voltage during sensor lightweight rubbing (a) and periodical pressing (b) is shown. During sensor rubbing voltage didn’t change significantly, it increased just by pressing sensor. Goal of the test was to determine the sensitivity of the system and activation threshold. Considering that some pressure of body is possible on sensor because of wearer’s movements during sleep, system’s activation threshold was set at 3V. Tests were carried out under experimental conditions. In order to examine and compare performance under realistic conditions, it is necessary to perform testing with a user group.

Textile displays

Using textile conductive yarns for partial replacement of traditional electronic materials, woven electroactive textiles were design to which electronic devices were attached afterwards. Designed textile displays represents electronic system embedding with integration technology (see Fig.2.1.). Displays prototypes are shown in Fig. 3.4.



a b

Fig.3.4. Textile displays: LED display II, LED display III

During experimental work specific weave was designed (LED display II) in order to get fabric with possibility to vary brightness of emitting light by textile structure. In its turn designed weave of LED display III contains long floats for electronic elements covering and integrating into textile structure without surface deformation, as well as it allows to isolate intersection point of vertical and horizontal electrical contacts into display.

Textile display can be used as output interface for different electronic systems, integrating it in clothing, accessories, room and auto interior etc. To ensure electrotextile protection from environmental conditions (like humidity), display can be insulated.

Insulation of textile light emitting display

Insulation of textile circuit is an important part of system that ensures wear and operating safety – protects electrical contacts and elements from short circuits, corrosion and impact of environmental conditions as well as protects wearer from electrical system. During research textile circuits’ insulation with three different silicon materials and one polyurethane film was done in order to provide information about electronic circuit insulation possibilities on textile surface, encouraging development of textile electronic system insulation method.

After wash test was concluded that waterproof insulation layer protects display samples from moisture presence, wherewith from short circuit in system and from corrosion as well. But it can't provide fully protection from mechanical forces – after washing some part of LEDs didn't work. Fig.3.5 and Fig.3.6 shows summary of results – emitted light intensity and number of working LEDs decreases in both cases (insulated and non-insulated samples), however trend line shows that average light intensity decrease faster in non-insulated samples.

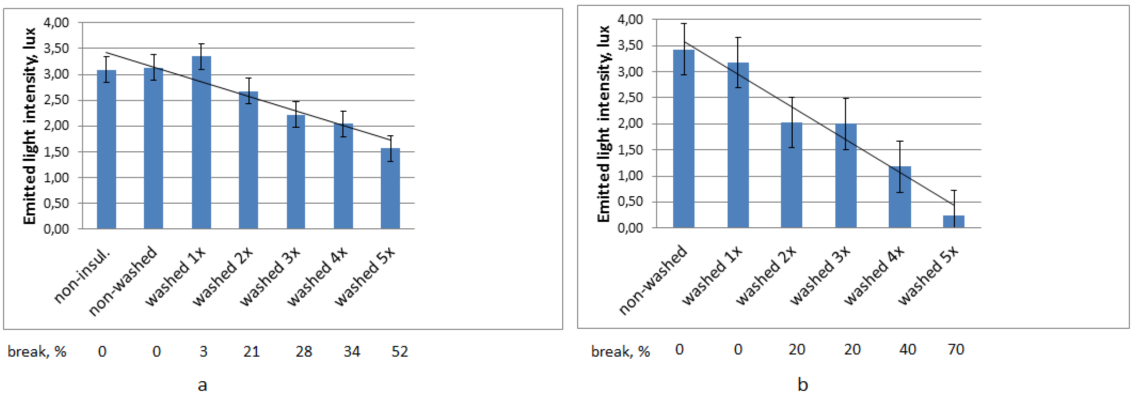


Fig.3.5. Change of light intensity and number of failed LEDs after washing for sample group N1: a – insulated samples; b – non-insulated samples

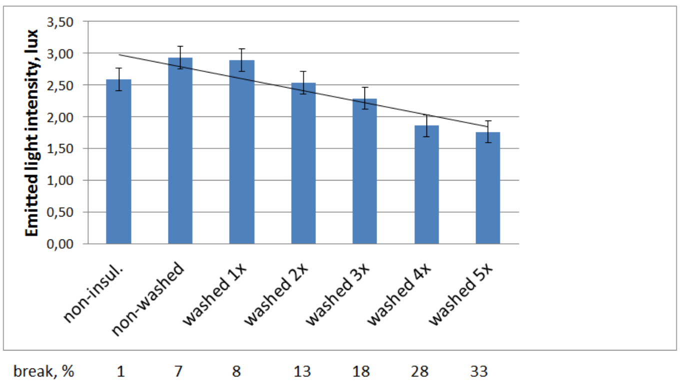


Fig.3.6: Change of light intensity and number of failed LEDs after washing for sample group N2 (insulated)

During coating process using liquid insulation material (in this case - silicone) it is necessary to conform electronic elements with fabric structure – it can have an impact on quantity of insulation materials and thickness of coating layer. Material type placed under samples during coating process is important as well. In its turn electronic elements integration into textile structure easies coating applying and ensures to make evener and thinner coating, fully insulating surface.

Both insulation materials are suitable for electronic insulation on textile surface. PU coating film is more suitable for textile circuits, where tension is not desired (including LED display) – film isn't flexible, during mechanical impacts it doesn't stretch with material and fixes material / yarns on place. In its turn silicone insulation suitable for textile circuits where tension is allowable, for example, stretch sensors, textile electrodes and so on.

In abrasion test silicone coated LED samples were more durable, but in washing test PU film laminated samples showed better results

For conductive traces in textile displays samples conductive yarn was selected with stable conductivity, which remains practically unchanged after insulation and washing.

Wherewith the electrical properties of the samples after insulation and washing tests didn't change significantly, the weak point was connection joints, which broke in some parts of sample due to impact of mechanical actions. In samples SMD LEDs were connected to conductive yarns, forming solder contacts directly on contact area of diode. Connected conductive yarns due to influence of mechanical impact can tear off LED's soldering terminal and in the result diode will not work anymore. In order to avoid this defect, it is necessary to add diode to the printed circuit board (PCB) substrate to get stable position of element. To retain flexibility of display, instead of hard PCB flexible PCB surface can be used (like film), as well as smaller size of diodes can be used (like 0806 or 0603 size SMD LED).

3.3. Electronic system design optimization

During research decision making methods *ELECTRE* and *AHP* were adapted for smart textile product electronic system evaluation and comparison. Previously designed smart jacket prototype [93] was analyzed by improving its electronic system design. Analyzed prototype represents electronic system embedding with block technology (see Fig.2.1.).

Prototype reacts to microclimate changes with the help of embedded electronics and signals about data of temperature and relative humidity under jacket. Electronic elements are embedded in jacket in a way that makes it possible to remove them before washing, therefore electronic elements are placed on removable layer.

During the development of the smart clothing it is important to consider design and arrangement of electronic elements in order to get functional, comfortable and ergonomic layout of electronic components in smart garment. Improving jacket prototype, external and internal zoning was analyzed and the most suitable zones for electronic elements placement in jacket were selected. Afterwards alternative variants of electronic element arrangement in jacket were designed. The aim of the research was to rank different variants of electronic element arrangement, to aggregate carefully the available information and to rank different variants of arrangement using a set of criteria as objectively as possible, using decision making method *ELECTRE*. Decision analysis helps better understand the environment in which the decision is made, and promote more informative decision. The results of analysis can be used to predict the stability of a variety of alternative decisions, sensitivity to small changes, as well as to structure the decision. Decision-making method provides algorithmic approach for decisions structuration and preference modeling, and as a result - an alternative ranking resulting from information provided by decision making person [94].

The prototype (P) and alternative designs (A, B, C, D, E, F) were considered in the analysis. Eight criteria were selected and each variant was evaluated according to each criterion. In the diagram of partial ranking on the set of alternatives (Fig.3.7.) is shown predominance of one alternative over the other. Dominant versions are B (predominance over 4 alternatives) and C (predominance over 3 alternatives).

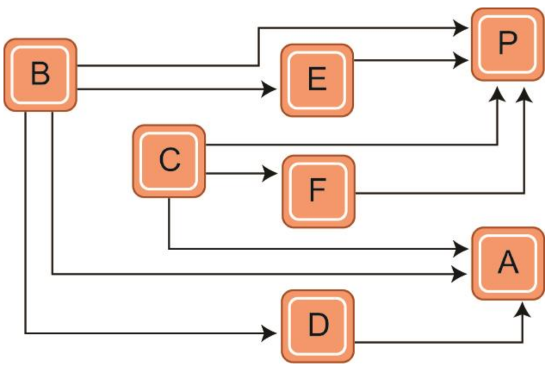


Fig.3.7. Partial ranking on the set of alternatives

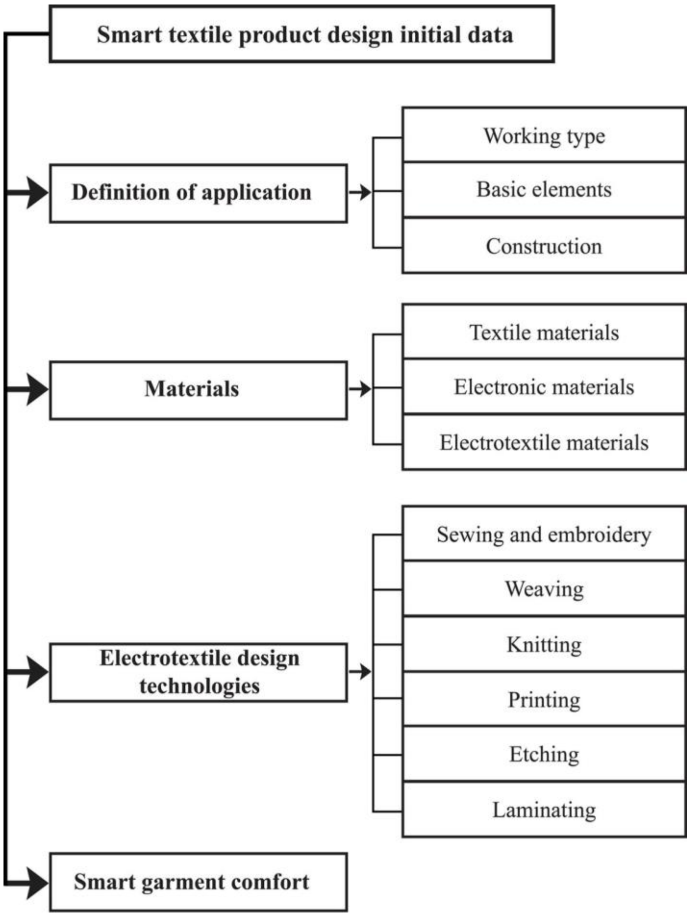
4. SMART TEXTILE PRODUCT DESIGN PROCESS MODEL

Smart clothing is a new type of apparel created by using a fusion technology that combines electronic engineering and apparel design, therefore during smart textile product design process interdisciplinary work must be done. Designers working on smart clothing should consider the multi-faceted factors in their design process, because smart textile product design process relevantly differs from traditional textile product design [68]. Therefore, for successful designing of smart clothing, it is prerequisite to modify the traditional apparel design process and to inform clothing / textile designer about this specific smart textile design process.

Based on theoretical information and experimental experience a structural diagram of smart textile product design works has been developed by laying emphasis on textile, electrical engineering and electrical textile technologies and characterizing their interaction from the point of view of choosing a relevant design solutions for smart textile products.

4.1. Smart textile product design initial data

According to the theoretical basis of smart textile products design (Chapter 1), structure of smart textile product design initial data was developed, which includes information about application, applicable materials, elektrotextile design technologies and smart garment comfort. Structure of smart textile product design initial data is shown in Fig. 4.1.



4.1. att. Structure of smart textile product design initial data

4.2. Smart textile product design process model

During research smart textile product design process model was developed, which is divided in two parts – textiles and electronics, describing model with three operating modes – textile engineering processes, electrical engineering processes and electrotextile engineering processes. Electrotextile engineering combines textile and electronic engineering technologies and is the most complex part of smart textile product development as it must combine materials with completely different structural properties. Smart textile product design process model is shown in Fig.4.2.

Links of elements in model characterize stages of smart textiles materials and technologies selection and process planning. Depending on the designed smart textile product type, model structure may change – according to the specifics of the product model can be shorten or extended.

Relatively design process model can be divided into 5 sections:

I Project preparation
II Initial data identification and materials selection
III Concept Analysis
IV Experimental technology
V Prototype evaluation

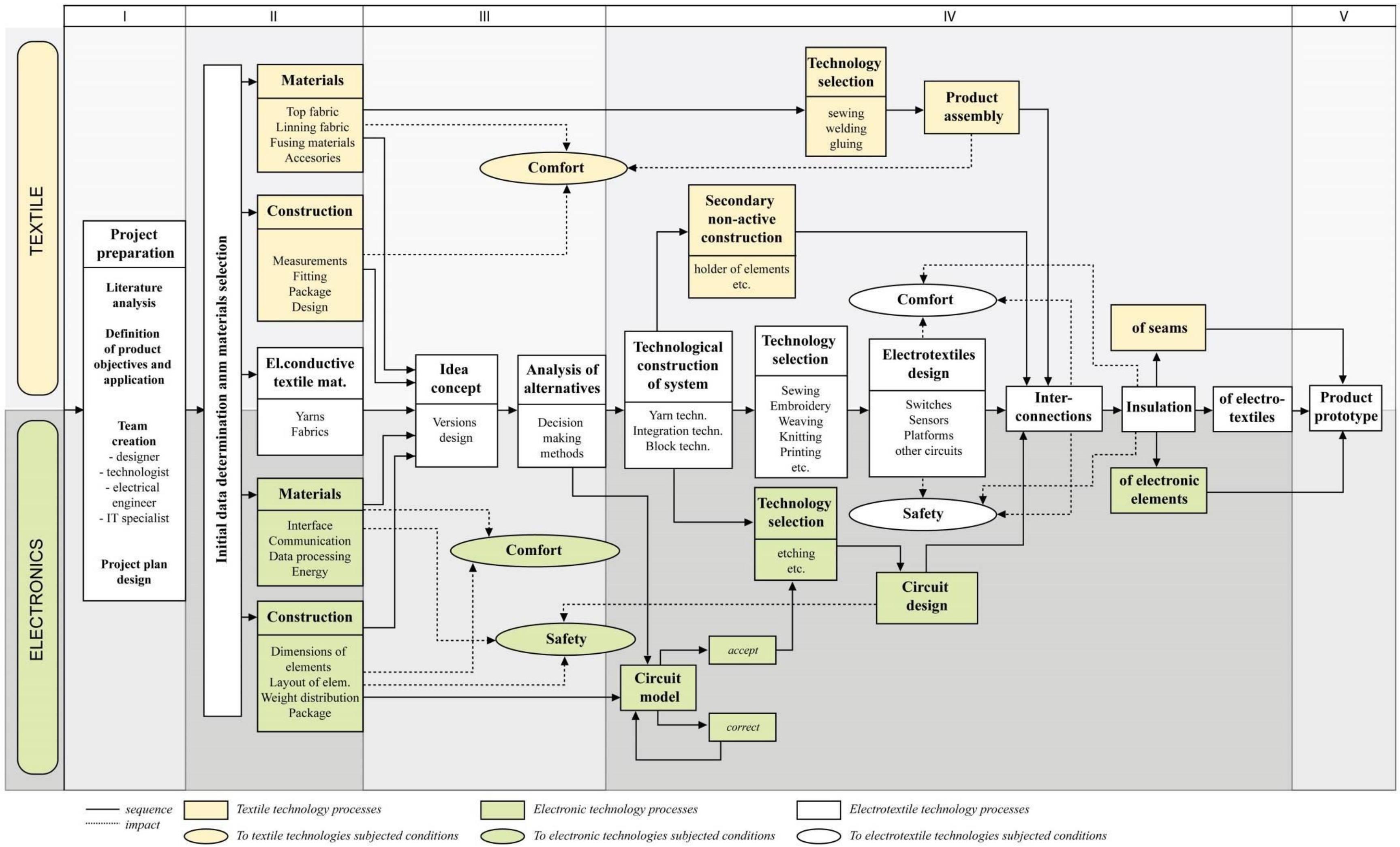


Fig. 4.2. Model of smart textile product design process

CONCLUSIONS AND RESULTS

Manufacturing of smart textile products is a new branch which improves the properties of traditional clothing/textiles and completes them with new functional properties. Such garments are used in different fields like sports, medicine, entertainment etc. In order to improve wearable electronics features, system connections should be high quality and reliable conductors of electricity and they should ensure traditional garment comfort. It is rather difficult to combine all these properties due to the different nature of electronic and textile components. During the last decade the development of electrotextiles has progressed, but still there are things which should be developed and improved. It is necessary to improve the process of designing smart textile products for the enhancement and more precise forecasting of their performance characteristics.

Experimental part of the work consists of four research stages, on which basis possibility of electronic systems embedding into textiles and clothing was analyzed, change of electrotextile properties affected by various processes was studied as well as features of smart textile product design process was explore.

During the study of electrically conductive yarns properties and its changes it was concluded that it can be affected by sewing process, external environment factors and washing. These characteristics can vary significantly among yarns, for example, in three washing cycles from 35% (yarn N3) to 622% (yarn N1). Therefore during the design of electronic circuitry it is necessary to take into consideration the changing nature of the conductive yarns and to use appropriate yarns in appropriate places. The main factors are the criticality and sensitivity of the circuit, as well as peak current consumption. Multi-ply conductive yarns are more durable and suitable for sewing/embroidery, such yarns produce better quality seams than single ply yarn does, which breaks and makes fuzzes during sewing what can cause short circuit. Single ply yarn shows the weakest results in wash test – it endures just for 6 cycles, afterwards electrical contact was lost.

Woven, sewn and embroidered electrotextile samples were designed and its structural affect on the electrical properties of the material as well as durability of interconnections was analyzed. It was found that durability of interconnections depends from both interconnection type and conductive yarn integration type into textile. For example, after washing test knot contacts in some parts formed weaker connection (decrease of conductivity by 24-63% after 1-10 washing cycles), but ceased contacts haven't been observed. In its turn conductivity change of soldered joints (decrease of conductivity by 3-59% after 1-10 washing cycles) was associated with the contact breaks, in unbroken contacts significant changes of electrical conductivity wasn't observed.

During research several electrotextiles were designed for various applications – light emitting displays and moisture sensors. Features of design process of samples were described. New textile display constructions were created combining fabric's aesthetic and functional design. Specific weave was designed (LED display II) in order to get fabric with possibility to vary brightness of emitting light by textile structure. In its turn designed weave of LED display III contains long floats for electronic elements covering and integrating into textile structure without surface deformation, as well as it allows to isolate intersection point of vertical and horizontal electrical contacts into display. Display with long floats for electronic elements covering was patented.

In insulation experiment textile circuits was covered with three different silicon materials and one polyurethane film. Although waterproof insulation layer protects display samples from moisture, it can't provide close and stable contact fixation. After washing emitted light intensity and number of working LEDs decreases in both cases (insulated and non-insulated samples), however trend line shows that average light intensity decrease faster in non-insulated samples.

Nocturnal alarm system was analyzed and recommendations for system improvement were developed. Sensor system circuit was designed and two sensor tests were performed: system activation test and false alarm test to determine the sensitivity of the system and activation threshold. In experiment two types of sensor were considered – sewn and woven sensor. Sewn sensor had better results in system activation test – moisture detection speed was faster, but woven sensor showed better results in false alarm test – it was less sensitive to perspiration simulation. After experiments it was found that the optimum switching threshold is 3V in case of 5V input voltage, which provides protection against false alarms, for example during intensive sweating.

During research decision making methods *ELECTRE* and *AHP* were adapted for smart textile product electronic system evaluation and comparison. Previously designed smart jacket prototype was analyzed and from six alternative variants of electronic element arrangement in jacket the most dominante versions were selected which could be used in further research work. The results of analysis can be used to predict the stability of a variety of alternative decisions, sensitivity to small changes, as well as to structure the decision.

Based on theoretical information and experimental experience a structural diagram of smart textile product design process has been developed for the enhancement and more precise forecasting of smart textile products performance characteristics. Model is divided in two parts – textiles and electronics, describing model with three operating modes – textile engineering processes, electrical engineering processes and electrotextile engineering processes. It can be divided into 5 sections - project preparation, initial data identification and materials selection, concept analysis, experimental technology and prototype evaluation. Links of elements in model characterize stages of smart textiles materials and technologies selection and process planning.

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