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# The Usage of Genetic Methods for Prediction of Fabric Porosity

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Additional information is available at the end of the chapter

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## 1. Introduction

Advanced fabric production demands developing strategies with regard to new fabric constructions in which sample-production is reduced to a minimum. It is clear that a new fabric construction should have the desired end-usage properties pre-specified as project demands. Achieving such a demand is a complex task based on our knowledge of the relations between the fabric constructional parameters and the predetermined fabric end-usage properties that fit the desired quality. Individual fabric properties are difficult to predict when confronting the various construction parameters, which can be separated into the following categories: raw materials, fabric structure, design, and manufacturing parameters.

Many attempts have been made to develop predictive models for fabric properties with different modelling tools. There are essentially two types of modelling tools: deterministic (mathematical models, empirical models, computer simulation models) and non-deterministic (models based on genetic methods, neural network models, models based on chaos theory and theory of soft logic), and each of them has its advantages and disadvantages [1].

Deterministic modelling tools present the heart of conventional science and have their basis in first principles, statistical techniques or computer simulations. Mathematical models offer a deep understanding of relations between constructional parameters and predetermined fabric property, but due some simplifying assumptions large prediction errors occur. Empirical models based on statistical techniques show a much better agreement with the real values but the problems with samples preparing, process repeatability, measurements errors and extrapolation occur. They usually refer to the one type of testing method of particular fabric property. The advantage of computer simulation models is their ability to capture the randomness inherent in fabric structure so the predicted values are very near the

real ones, but on the other hand they require numerous fabric samples data. The problem with extrapolation still remains. In general, when deterministic modelling is used, the obtained models are the results of strict mathematical rules and/or the models are set in advance. In this case the goal is to discover merely a set of numerical coefficients for a model whose form has been pre-specified. However, nowadays more and more processes and systems are modelled and optimized by the use of non-deterministic approaches. This is due to the high degree of complexity of the systems, and consequently, inability to study them successfully by the use of conventional methods only. In non-deterministic modelling of systems, no precise and strict mathematical rules are used [2, 3, 4, 5, 6, 7]. For example, in genetic programming, no assumptions about the form, size, and complexity of models are made in advance. They are left to the stochastic, self-organized, intelligent, and non-centralized evolutionary processes [1, 8].

Fabrics are porous materials having different porous structures as the consequence of different manufacturing techniques needed to interlace the fundamental structural elements, e.g. fibres, yarns or layers, into fibrous assembly. Fabric porosity strongly determines important physical, mechanical, sorptive, chemical, and thermal properties of the fabrics such as mechanical strength, thermal resistance, permeability (windproofness, breathability), absorption and adsorption properties (wicking, wetting), translucence, soiling propensity, UV light penetration, sound absorption ability, etc. [9, 10]. Knowledge about the fabric's porous structure is, therefore, an important step when characterising fabrics, in order to predict their behaviour under different end-usage conditions regarding a product. Hence, if porosity is estimated or predicted then when developing a new product the desired porosity parameters can be set in advance on the basis of selecting those fabric constructional factors that have an effect on porosity and, in this way sample production trials could be reduced.

This chapter gives some basic information about the porosity, porosity parameters of woven and nonwoven fabrics, and the results of the studies dealing with the prediction of porosity parameters of two types of fabrics, e.g. woven fabrics made from the 100% cotton staple yarns and needle-punched nonwovens made from the mixture of viscose/polyester fibres, using nondeterministic modelling tools, e.g. genetic programming (GP) and genetic algorithms (GA), respectively.

## 2. Porosity and porosity parameters

Flat textile materials, e.g. fabrics, are porous materials which allow the transmission of energy and substances and are therefore interesting materials for different applications. In general, they are used for clothing, interior and wide range of technical applications. Fabric as porous barrier between the human body and environment should support heat and water vapour exchange between the body and environment in order to keep the body temperature within the homeostasis range. Besides thermo-physiological protection, fabrics also play an important role by heat protection due to the flames or convection heat, contact heat, radiant heat as well as due to the sparks and drops of molten metal, hot gases and vapours [11].

Fabrics protect users against micro-organisms, pesticides, chemicals, hazardous particles and radiations (radioactive particles, micro-meteorites, X-rays, micro-waves, UV radiation, etc.). They act very important role also by environmental protection as filters for air and water filtrations, sound absorption and isolation materials against noise pollution, adsorption materials for hazardous gas pollution, etc. [10, 12, 13]. By all mentioned applications dedicated to absorption, desorption, filtration, drainage, vapours transmission, etc., the essential constructional parameter that influences fabric efficiency to protect human or environment is porosity. The fabric in a dry state is a two-phase media which consists of the fibrous material – solid component and void spaces containing air – gas (void) component. The porosity of a material is one of the physical properties of the material and describes the fraction of void space in the material. The porosity (or void volume fraction) is expressed as coefficient ranging between 0 and 1 or as percentage ranging between 0% and 100% (by multiplying the coefficient by 100). Mathematically, the porosity is defined as the ratio of the total void space volume to the total (or bulk) body volume [14, 15]:

$$\varepsilon = \frac{V_v}{V} \quad (1)$$

where,  $\varepsilon$  is the porosity expressed as coefficient,  $V_v$  is the volume of the total void space in  $\text{cm}^3$ , and  $V$  is the total or bulk body volume in  $\text{cm}^3$ . The total volume of the body consists of the volumes of the solid and void components as follows:

$$V = V_v + V_s \quad (2)$$

where,  $V$  is the total volume of the body in  $\text{cm}^3$ ,  $V_v$  is the volume of void component in  $\text{cm}^3$ , and  $V_s$  is the volume of solid component in  $\text{cm}^3$ . If the volume of void component is exposed from the Equation 2, the Equation 1 can be further written as follows:

$$\varepsilon = \frac{V_v}{V} = \frac{V - V_s}{V} = 1 - \frac{V_s}{V} = 1 - \beta \quad (3)$$

$$\beta = \frac{V_s}{V} \quad (4)$$

where,  $\beta$  is the fulfilment (or solid volume fraction) which describes the fraction of solid component volume in the material expressed as coefficient ranging between 0 and 1 or as percentage. If we take into account the common equation for material density (Equation 5), and assume that the mass of the material is actually the mass of solid component ( $m_s = m_b$ ), the Equation 3 could be further written in the form of Equation 6:

$$\rho = \frac{m}{V} \quad (5)$$

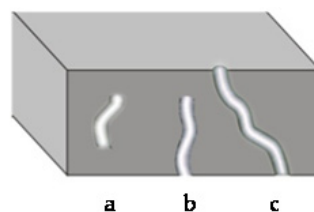
$$\varepsilon = 1 - \frac{V_s}{V} = 1 - \frac{m_s \rho_b}{\rho_s m_b} = 1 - \frac{\rho_b}{\rho_s} \quad (6)$$

where,  $\varepsilon$  is the porosity expressed as coefficient,  $V_s$  is the volume of solid component in  $\text{cm}^3$ ,  $V$  is the volume of the body (or bulk volume) in  $\text{cm}^3$ ,  $m_s$  is the mass of solid component in g,  $m_b$  is the mass of the body (or bulk mass) in g,  $\rho_b$  is the bulk density in  $\text{g}/\text{cm}^3$ , and  $\rho_s$  is the density of solid component in  $\text{g}/\text{cm}^3$ .

In this way exactly defined porosity of the material is useful parameter, only, when materials with the same porous structure are compared, and gives an indication which material possesses more void space in the bulk volume. It does not give any information about the porous structure of the material, so it is an insufficient parameter for describing fibre assembly characteristics [16]. Namely, the materials with the same porosity could have very different porous structure and consequently, in the case of fabrics, different protection, filtration, sound absorption, etc., properties; so the need to define porous structure and some other porosity parameters is essential. From the theoretical point of view, the porosity parameters could be easily determined on the basis of an ideal geometrical model of the material porous structure. The simpler models consider that all pores, whatever their shape, are the same and regularly arranged in a fibre assembly [16, 17]. Ideal models are based also on some other simplifying assumptions depending on the fibre assembly type. Porosity parameters calculated on the basis of ideal models of porous structures are usually not in a good correlation with the real porosity parameters. Real porous media generally have rather complex structures that are relatively difficult to define. But the advantage of ideal geometric models of porous structures is the possibility to understand the influence of porous structure on some end-usage properties of the material, which is crucial by a new product planning.

The fundamental building elements of the material porous structure are pores (also capillaries, channels, holes, free volume) [15, 18]. Pores are void spaces within the material which are separated between each other, and are classified [19, 20]:

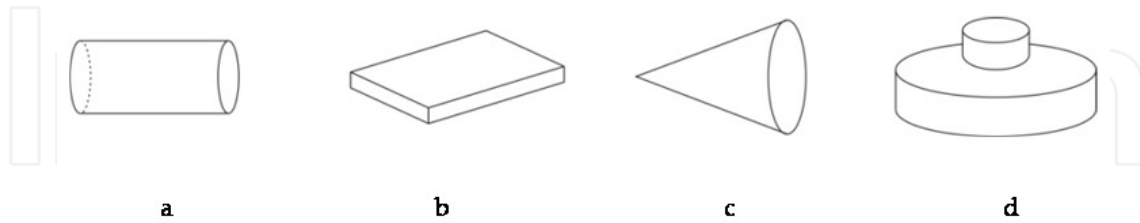
1. according to the position in the material into:
  - a. inter-pores, e.g. pores which lie between the structural elements of the material,
  - b. intra-pores, e.g. pores which lie within the structural element of the material;
2. according to the pore width (the shortest pore diameter) into:
  - a. macropores whose pore-width is greater than 50 nm,
  - b. mesopores whose pore-width lies in the range between 2 and 50 nm, and
  - c. micropores with the pore-width lower than 2 nm;
3. according to the fluid accessibility into (Figure 1):
  - a. closed pores being inaccessible for fluid flow or surroundings,
  - b. blind pores which are accessible for fluid but terminate inside the material and prevent fluid flow, and
  - c. open (or through) pores which are open to external surface and permit fluid flow;



**Figure 1.** Types of pores according to the fluid accessibility

4. according to the pore shape into (Figure 2):

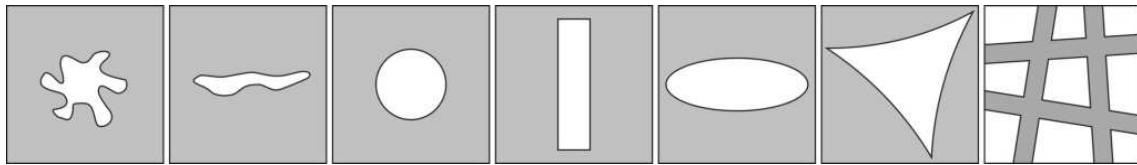
- a. cylindrical pores,
- b. slit-shape pores,
- c. cone-shape pores, and
- d. ink bottle pores;



**Figure 2.** Types of pores according to the pore shape [19]

5. according to the geometry of pore-cross section into (Figure 3):

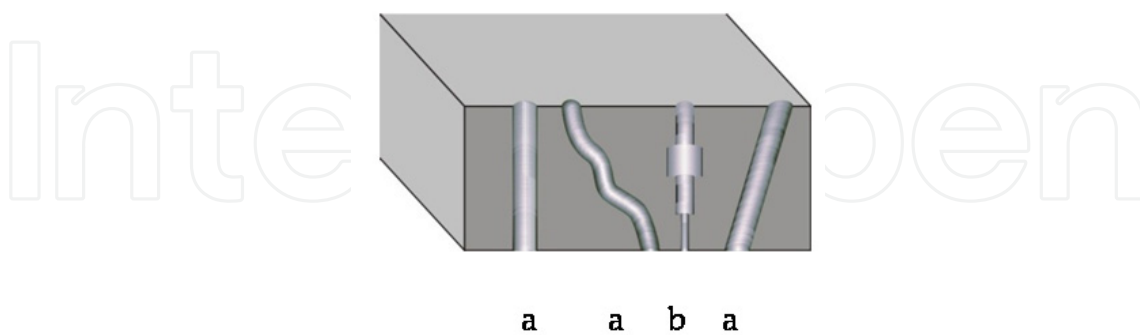
- a. pores with geometrically regular cross-sectional shape and
- b. pores with geometrically irregular cross-sectional shape,



**Figure 3.** Different shapes of pore cross-sections [20]

6. according to the uniformity of pore cross-section over the pore length into (Figure 4):

- a. pores with a permanent cross-section,
- b. pores with a different cross-sections and for which different diameters are defined (the most constricted, the largest, the mean pore diameters).



**Figure 4.** Pores with permanent (a) and non-permanent (b) cross-sections over their length

Four groups of pore descriptors, e.g. size, shape, orientation, and placement, are defined as important parameters [21]. Pores can be mathematically assessed on the basis of known model of pores geometry and constructional parameters of the material with the following parameters: the number of pores, pore size, pore volume, pore surface area, pore length, etc.

On the basis of an ideal geometrical model of porous structure, the pore size distribution which is also an important parameter of material porous structure can not be assessed while the pores in geometrical model are usually assumed to be the same sizes. Such situation rarely occurs in the real fabrics. The further considerations of ideal geometrical models of material porous structures and porosity parameters will be focused on different types of fabrics.

Fabrics are flat textile materials which are produced by different manufacturing techniques using different fibrous forms of input material (or structural element), and consequently having different porous structures. Following basic types of fabrics are known (Figure 5):

- woven fabrics which are made by interlacing vertical warp and horizontal weft yarns at right angles to each other,
- knitted fabrics which are made by forming the yarn into loops and their interlacing in vertical (warp-knitted fabrics) or horizontal (weft-knitted fabrics) direction,
- nonwoven fabrics which are produced from the staple fibres, filaments or yarns by different web-forming, bonding and finishing techniques.



**Figure 5.** 2-D schematic presentations of woven-, knitted-, and nonwoven (made from staple fibres) fabrics

While this chapter is focused on the genetic methods in order to predict porosity of woven and nonwoven fabrics, only those types of fabrics and their ideal geometric models of porous structure will be presented.

## 2.1. Woven fabric's ideal geometric model of porous structure

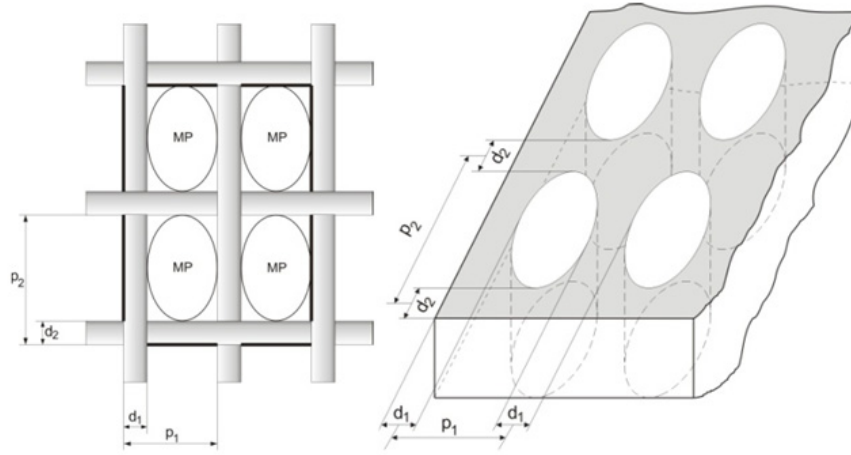
When a woven fabric is treated as a three dimensional formation, different types of pores are detected [22, 23, 24]: 1. inter-pores, e.g. the pores which are situated between warp and weft yarns (macropores, interyarn pores) and pores which are situated between fibres in the yarns (mesopores, interfiber/intrayarn pores), 2. intra-pores, e.g. the pores which are situated in the fibres (micropores, intrafiber pores). The structure and dimensions of the inter- or intrayarn pores are strongly affected by the yarn structure and the density of yarns in the woven structure [22]. As fibrous materials, woven fabrics have, with regard to knitted fabrics or nonwovens, the most exactly determined an ideal geometrical model of a macroporous structure in the form of a tube-like system, where each macropore has a cylindrical shape with a permanent cross-section over all its length (Figure 6) [25]. Because the warp density is usually greater than the weft density, the elliptical shape of the pore cross-section

is used to represent the situation in Figure 6. Macropores are opened to the external surface and have the same cross-section area. They are separated by warp or weft yarns, and are uniformly distributed over the woven fabric area.

The primary constructional parameters of woven fabrics which alter the porous structure are:

- yarn fineness, e.g. the mass of 1000 meter of yarn from which the yarn diameter can be calculated,
- type of weave, e.g. the manner how the yarns are interlaced. It has an effect on the pore size as well as on the shape of pore cross-section [26],
- the number of yarns in length unit (warp and weft densities), which directly alters the pore size.

When fibre properties (fibre density, dimension, and shape) are different, two woven fabrics with similar woven structures and geometrical configurations can have distinctly different porosity [22].



**Figure 6.** 2D and 3D presentations of an ideal model of the porous structure of a woven fabric [27, 28] ( $d$  – yarn thickness,  $p$  – yarn spacing, MP - macropore; 1, 2 indicates warp and weft yarns, respectively)

To compare woven fabrics with porosity, the following porosity parameters can be calculated on the basis of the woven fabric primary constructional parameters and the ideal model of porous structure in the form of a tube-like system:

- (total) porosity by using Equation 6 where the bulk density of the material is actually the woven fabric density and the density of solid component is the yarn density. If the fibre volume fraction (yarn packing factor) is exposed from the Equation 7 which represents the yarn diameter calculation, and then inserted in Equation 8 by assuming Equation 9 for woven fabric density at the same time, the porosity of woven fabrics can be then written in the form of Equation 10:

$$d = \sqrt{\frac{4T}{10^5 \pi \cdot \rho_{yarn}}} = \sqrt{\frac{4T}{1000 \cdot \pi \cdot \rho_{fib} \cdot \beta_{fib}}} \quad (7)$$

$$\rho_{yarn} = \rho_{fib} \cdot \beta_{fib} \quad (8)$$

$$\rho_{fab} = \frac{m}{D \cdot 1000} \quad (9)$$

$$\varepsilon = 1 - \frac{\rho_b}{\rho_s} = 1 - \frac{\rho_{fab}}{\rho_{yarn}} = 1 - \frac{100 \cdot m \cdot d^2 \cdot \pi}{D \cdot 4 \cdot T} \quad (10)$$

where,  $d$  is the yarn diameter in cm,  $T$  is the yarn fineness in tex,  $\rho_{yarn}$  is the yarn bulk density in g/cm<sup>3</sup>,  $\rho_{fib}$  is the fibre density in g/cm<sup>3</sup>,  $\beta_{fib}$  is the fibre volume fraction (or yarn packing factor),  $\rho_{fab}$  is the woven fabric bulk density in g/cm<sup>3</sup>,  $m$  is the woven fabric mass per unit area in g/m<sup>2</sup>,  $D$  is the woven fabric thickness in mm,  $\rho_b$  is the body bulk density in g/cm<sup>3</sup>, and  $\rho_s$  is the density of solid component in g/cm<sup>3</sup>. It is worth to mention that in this way defined porosity refers to all types of pores regarding their position in the woven fabric, e.g. inter- and intra-pores;

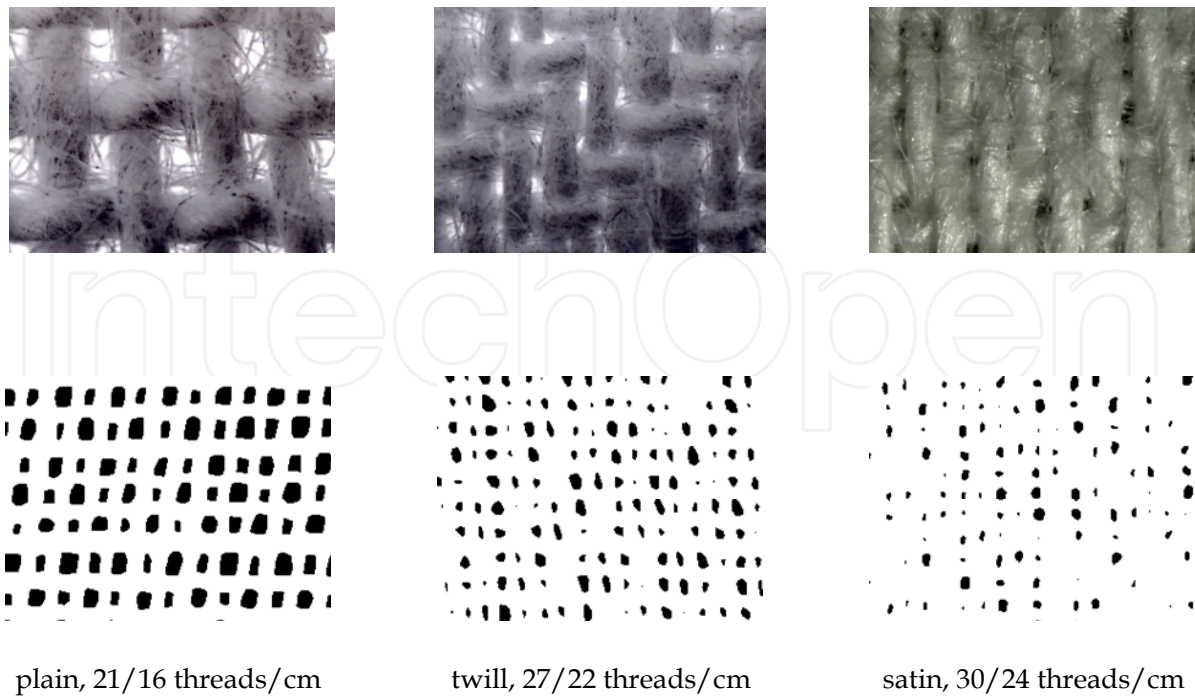
- area of pore cross-section which refers only on macropores in a woven fabric. The ideal model of woven fabric porous structure is based on the assumption that macropores have cylindrical shape with circular cross-section. In real woven fabrics, the macropore cross-section shape is more likely to be irregular rather regular (Figure 7) [26]. The shape of pore cross-section and consequently the area of pore cross-section depend on the type of yarns used. Woven fabrics made from filament yarns have pure macropores with rectangular cross-sections, whilst woven fabrics made from staple yarns have a small percentage of pure macropores, some of partly latticed macropores as well as fully latticed macropores (as the consequence of the phenomenon of latticed pores) with mostly irregular cross-sections. The area of pore cross-section also depends on the phenomenon of changing the position of warp threads according to the longitudinal fabric axis and the phenomenon of thread spacing irregularity [28]. For the theoretical calculations of the macropore cross-section area three types of regular pore cross-section shapes are taken into account, e.g. circular (Equation 11), rectangular (Equation 12) and elliptical (Equation 13) as follows:

$$A_{p/circular} = \frac{\pi}{16} (p_1 + p_2 - d_1 - d_2)^2 = \frac{\pi}{16} \left( \frac{10}{g_1} + \frac{10}{g_2} - d_1 - d_2 \right)^2 \quad (11)$$

$$A_{p/rectangular} = (p_1 - d_1) \cdot (p_2 - d_2) = \left( \frac{10}{g_1} - d_1 \right) \cdot \left( \frac{10}{g_2} - d_2 \right) \quad (12)$$

$$A_{p/elliptical} = \frac{\pi}{4} \cdot (p_1 - d_1) \cdot (p_2 - d_2) = \frac{\pi}{4} \left( \frac{10}{g_1} - d_1 \right) \cdot \left( \frac{10}{g_2} - d_2 \right) \quad (13)$$

where,  $A_p$  is the area of macropore cross-section in mm<sup>2</sup>,  $p$  is the yarn spacing in mm,  $d$  is the yarn diameter in mm,  $g$  is the number of yarns per unit length in threads/cm, and subscripts 1 and 2 indicate warp and weft yarns, respectively;



**Figure 7.** Real and binary images of the pore cross-section shape and the number of pores in real woven fabrics (magnification of binary images: 20 x, magnification of real images: 80 x, yarn fineness: 36 tex, fabric relative density: 83 %)

- number of macropores in the area unit (pore density). It can be seen from Figure 7, that one macropore belongs to one warp yarn and one weft yarn, so the number of macropores can be calculated on the basis of warp and weft densities using Equation 14:

$$N_p = g_1 \cdot g_2 \quad (14)$$

where,  $N_p$  is the pore density in pores/cm<sup>2</sup>,  $g_1$  is the warp density in threads/cm, and  $g_2$  is the weft density in threads/cm;

- open porosity (open area) which describes the fraction of macropore cross-section area in the area unit of woven fabric. If we assume elliptical macropore cross-section area (Figure 7), the open porosity is calculated as follows:

$$\varepsilon_{open} = \frac{A_p}{A_p + A_y} = \frac{\pi(p_1 - d_1) \cdot (p_2 - d_2)}{4 \cdot p_1 \cdot p_2} \quad (15)$$

where,  $\varepsilon_{open}$  is the open porosity,  $A_p$  is the macropore cross-section area in mm<sup>2</sup>,  $A_y$  is the projection area of warp and weft yarns, which refers to one macropore in mm<sup>2</sup>,  $p$  is the yarn spacing in mm,  $d$  is the yarn diameter in mm, and subscripts 1 and 2 indicate warp and weft yarns, respectively. Open porosity can be calculated also on the basis of cover factor (Equation 16) or pore density (Equation 17) [26, 29]:

$$\varepsilon_{open} = 1 - K = 1 - \left[ \frac{\left( d_1 g_1 + d_2 g_2 - \left\{ \frac{d_1 d_2 g_1 g_2}{10} \right\} \right)}{10} \right] \quad (16)$$

$$\varepsilon_{open} = N_p \cdot A_p \quad (17)$$

where,  $\varepsilon_{open}$  is the open porosity,  $K$  is the woven fabric cover factor,  $d$  is the yarn diameter in mm,  $g$  is the warp/weft density in threads/cm,  $N_p$  is the pore density in pores/cm<sup>2</sup>,  $A_p$  is the area of macropore cross-section in cm<sup>2</sup>, and subscripts 1 and 2 indicate warp and weft yarns, respectively;

- equivalent macropore-diameter. If we assume that macropore has cylindrical shape, then the area of macropore cross-section is equal to the area of circle with radius  $r$  (Equation 18). Equivalent macropore diameter is the diameter of macropore with circular cross-section whose area is the same as the area of the macropore with irregular cross-section shape (Equation 19) [30].

$$A_{circle} = \pi \cdot r^2 = \frac{\pi \cdot d^2}{4} \quad (18)$$

$$d_e = \sqrt{\frac{4 \cdot A_p}{\pi}} \quad (19)$$

where,  $A_{circle}$  is the circular cross-section macropore area in mm<sup>2</sup>,  $r$  is the macropore radius in mm,  $d$  is the macropore diameter in mm,  $d_e$  is the equivalent macropore diameter in mm, and  $A_p$  is the macropore cross-section area of macropore with irregular shape in mm<sup>2</sup>;

- maximal and minimal macropore diameters which refer to the elliptical shape of macropore cross-section. In the case where warp density is greater than weft density the maximal diameter is equal to  $p_2 - d_2$ , while minimal diameter is equal to  $p_1 - d_1$  (Figure 7);
- macroporosity which describes the portion of macropore volume in volume unit of woven fabric. In general, it is defined using Equation 20. In the case of the elliptical macropore cross-section shape, the macroporosity, defined with Equation 21, is the same as open porosity:

$$\varepsilon_{macro} = \frac{V_p}{V_p + V_y} = \frac{A_p \cdot D}{p_1 \cdot p_2 \cdot D} = \frac{A_p}{p_1 \cdot p_2} \quad (20)$$

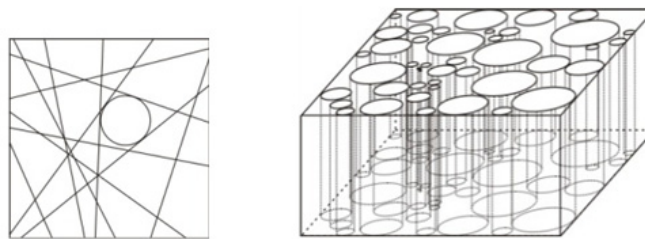
$$\varepsilon_{macro} = \frac{V_p}{V_p + V_y} = \frac{\pi(p_1 - d_1) \cdot (p_2 - d_2) \cdot D}{4 \cdot p_1 \cdot p_2 \cdot D} = \frac{\pi(p_1 - d_1) \cdot (p_2 - d_2)}{4 \cdot p_1 \cdot p_2} = \varepsilon_{open} \quad (21)$$

where,  $\varepsilon_{macro}$  is the macroporosity,  $V_p$  is the macropore volume in cm<sup>3</sup>,  $V_y$  is the volume of warp and weft yarns which refers to one macropore in cm<sup>3</sup>,  $p$  is the yarn spacing in mm,  $d$  is

the yarn diameter in mm,  $D$  is the woven fabric thickness in mm,  $A_p$  is the macropore area in  $\text{mm}^2$ ,  $\varepsilon_{\text{open}}$  is the open porosity, and subscripts 1 and 2 indicate warp and weft yarns, respectively.

## 2.2. Nonwoven fabric's ideal geometric model of porous structure

The porous structure of nonwoven fabric is a result of nonwoven construction (the type and properties of fibres or yarns as input materials, fabric mass, fabric thickness, etc.) as well as technological phases, e.g. the type of web production, bonding methods and finishing treatments. According to several different methods to produce non-woven fabrics having consequently very different porous structure, the ideal geometric model of porous structure in the form of tube-like system is partially acceptable only by those nonwovens which are thin and translucent, e.g. light polymer-laid nonwovens and some thin spun-laced or heat-bonded nonwovens (Figure 8). Such model is based on the assumptions that fibres having the same diameter are distributed only in the direction of fabric plane and the distance between fibres and the length of individual fibres is much greater than the fibre diameter. Xu [21] found out that in most nonwoven fabrics, pore shape is approximately polygonal and that pores appear more circular when the fabric density increases. Pore orientation to some extent relates to fibre orientation. If pores are elongated and predominantly oriented in one direction, fibres are likely to be oriented in that direction. The variation in pore size is inherently high. Some regions may contain more pores than others or may have larger pores than those in other regions.



**Figure 8.** 2D and 3D presentations of an ideal model of the porous structure of a nonwoven fabric (with detail to define opening diameter of pore by 2D presentation)

The primary constructional parameters of nonwoven fabrics which alter the porous structure are:

- fibre fineness, e.g. the mass of 1000 meter of fibre, from which the fibre diameter can be calculated,
- web mass per unit area and
- web thicknesses.

To compare nonwoven fabrics with porosity, the following porosity parameters can be calculated on the basis of the nonwoven fabric primary constructional parameters and the ideal model of porous structure in the form of a tube-like system:

- (total) porosity by using Equation 6 where the bulk density of the material is actually the nonwoven fabric density and the density of solid component is the fibre density. The nonwoven fabric density is calculated on the basis of primary nonwoven constructional parameters, e.g. fabric mass and thickness using Equation 9 where index fab in this case refers to the nonwoven fabric. Substituting Equation 9 into Equation 6, final Equation 22 of nonwoven porosity which refers to inter- (pores between fibres in nonwovens) and intra-pores (pores inside the fibres) is obtained:

$$\varepsilon = 1 - \frac{\rho_b}{\rho_s} = 1 - \frac{\rho_{fab}}{\rho_{fib}} = 1 - \frac{m_{fab}}{D_{fab} \cdot \rho_{fib} \cdot 1000} \quad (22)$$

where,  $\varepsilon$  is the nonwoven fabric porosity,  $\rho_b$  is the body bulk density in g/cm<sup>3</sup>,  $\rho_s$  is the density of solid component in g/cm<sup>3</sup>,  $\rho_{fab}$  is the nonwoven fabric density in g/cm<sup>3</sup>,  $\rho_{fib}$  is the fibre density in g/cm<sup>3</sup>,  $m_{fab}$  is the nonwoven fabric mass per unit area in g/m<sup>2</sup>, and  $D_{fab}$  is the nonwoven fabric thickness in mm;

- opening diameter which is the diameter of the maximum circle that can fit in a pore (Figure 8). It is predicted on the basis of nonwoven fabric constructional parameters and refers to the heat-bonded nonwoven fabrics, as follows [17, 21]:

$$d_o = \frac{1}{\sqrt{C} \cdot L} - d_{fib} \quad (23)$$

$$C = \frac{D_{fab}}{d_{fib}} \quad (24)$$

$$L = \frac{8 \cdot m_{fab}}{\pi \cdot D_{fab} \cdot d_{fib} \cdot \rho_{fib}} \quad (25)$$

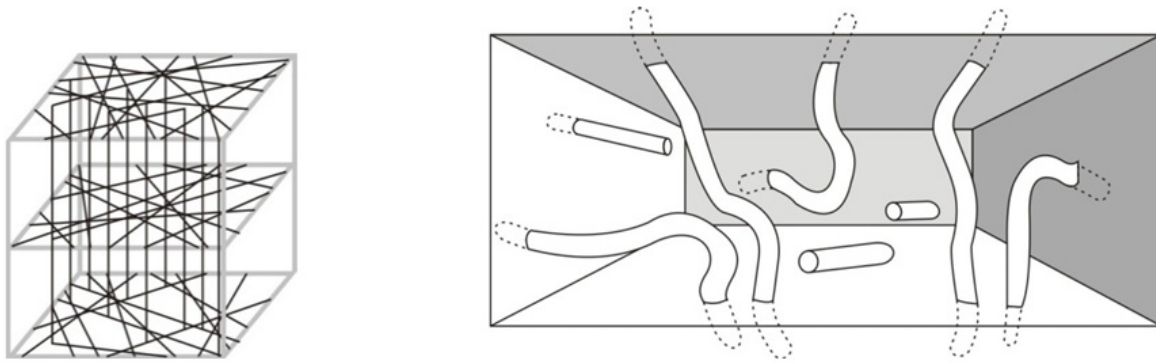
where,  $d_o$  is the opening diameter in  $\mu\text{m}$ ,  $C$  is the thickness factor,  $L$  is the specific total length of fibres per nonwoven unit area in mm<sup>-1</sup>,  $d_{fib}$  is the fibre diameter in  $\mu\text{m}$ ,  $D_{fab}$  is the nonwoven thickness in mm,  $m_{fab}$  is the nonwoven fabric mass per unit area in g/m<sup>2</sup>, and  $\rho_{fib}$  is the fibre density in g/cm<sup>3</sup>;

- average area of pore cross-section which is for un-needled fabrics (e.g. fabrics made of layers of randomly distributed fibres) predicted using Equation 26 [17]:

$$A_p = \frac{\pi \cdot \varepsilon \cdot d_{fib}^2}{(1 - \varepsilon)^2} \quad (26)$$

where,  $A_p$  is the average area of pore cross-section in mm<sup>2</sup>,  $\varepsilon$  is the porosity, and  $d_{fib}$  is the fibre diameter in  $\mu\text{m}$ . On the basis of calculated average area of pore-cross-section, the equivalent pore diameter is then calculated using Equation 19.

Needle-punched nonwoven fabric is a sheet of fibres made by mechanical entanglement, penetrating barbed needles into a fibrous mat [31]. Needle-punched nonwovens represent the largest segment of filtration materials used as dust filters [32]. The geometrical model of three-dimensional needle-punched nonwoven fabric proposed by Mao & Rusell [33], is also known from the literature, and it is constructed on a two-dimensional fibre orientation within the fabric plane, with interconnecting fibres oriented in the z-direction (Figure 10). Such model relies on the following basic assumptions: 1. the fibres in the fabric have the same diameter, and a fraction of the fibres is distributed horizontally in the two-dimensional plane, the rest are aligned in the direction of the fabric thickness, 2. fibre distribution in both the fabric plane and the z-direction is homogeneous and uniform, 3. in each two-dimensional plane, the number of fibres oriented in each direction is not the same, but obeys the function of the fibre orientation distribution  $\Omega(\alpha)$ , where  $\alpha$  is the fibre orientation angle, 4. the distance between fibres and the length of individual fibres is much greater than the fibre diameter. The basic porosity parameters which are based on the mentioned geometrical model of needle-punched nonwoven fabric are still difficult to define due to the fact that in each fabric planes fibres lie in different direction and in this way produce pores with different orientations, diameters, connectivity and accessibility to fluid flow (Figure 9). The only porosity parameters that are calculated from such model are:



**Figure 9.** Geometrical models of needle-punched nonwoven fabric and porous structure [14, 34]

- total porosity (Equation 22) and
- mean pore diameter which is deduced from the fibre radius and porosity according to the following relation proposed by White [34]:

$$d_p = \frac{\varepsilon}{1 - \varepsilon} \cdot \frac{d_{fib}}{2} \quad (27)$$

$$d_{fib} = 35.68 \sqrt{\frac{T}{\rho_{fib}}} \quad (28)$$

where,  $d_p$  is the mean pore diameter in  $\mu\text{m}$ ,  $\varepsilon$  is the nonwoven fabric porosity,  $d_{fib}$  is the fibre diameter in  $\mu\text{m}$ ,  $T$  is the fibre linear density in tex, and  $\rho_{fib}$  is the fibre density in  $\text{g/cm}^3$ .

Three kinds of pores may be present in needle-punched nonwoven fabrics, namely, closed pores, open pores, and blind pores. The important pore structure characteristics of needle-punched nonwoven fabrics as filter media are the most constricted open pore diameter (smallest detected pore diameter), the largest pore diameter (bubble point pore diameter), and mean pore diameter (mean flow pore diameter) [35].

### 3. The usage of genetic programming to predict woven fabric porosity parameters

Porosity parameters based on an ideal geometrical model of porous structure give woven fabric constructor some useful information about porosity by developing a new product, but they are not in a good agreement with the experimental values. In order to balance the difference between the theoretical and experimental values of porosity parameters, genetic programming was used to develop models for predicting the following macro-porosity parameters of woven fabric: the area of macro-pore cross-section, macro-pore density, open porosity, and equivalent macro-pore diameter. The genetic programming is a variant of evolutionary algorithm methods described in many sources (e.g., [2, 3, 4]). The basic information on the evolutionary algorithms is given at the beginning of the section 4. We implemented Koza's variant of genetic programming [2]. In our research, the independent input variables (the set of terminals) were: yarn fineness  $T$  (tex), weave value  $V$ , fabric tightness  $t$  (%) and denting  $D$  (ends/dent in the reed). The set of terminals also included random floating-point numbers between  $-10$  and  $+10$ . Variegated reed denting was treated as an average value of treads, dented in the individual reed dent. The dependent output variables were: area of macro-pore cross-section  $A_p$  ( $10^{-3}$  mm<sup>2</sup>), pore density  $N_p$  (pores/cm<sup>2</sup>), and equivalent macro-pore diameter ( $\mu$ m). For all modelling, the initially set of functions included the basic mathematical operations of addition, subtraction, multiplication, and division. In the case of modelling the area of macro-pore cross-section and pore density the initially set of functions also included a power function, whereas the set of functions for modelling of equivalent macro-pore diameter included an exponential function. We then used the genetic programming system to evolve appropriate models consist of above-mentioned sets of terminals and functions. Open porosity was calculated on the basis of predicted values of the area of macro-pore cross-section and macro-pore density and Equation 17. The equivalent macro-pore diameter was calculated on the basis of predicted values of the area of macro-pore cross-section using Equation 19. The fitness measure for modelling by genetic programming was exactly the same as defined by Equation 33 in section 4. The goal of the modelling was to find such a predictive model in a symbolic form, that Equation 33 would give as low an absolute deviation as possible.

The evolutionary parameters for modelling by genetic programming were: population size 2000, maximum number of generations to be run 400, probability of reproduction 0.1, probability of crossover 0.8, probability of mutation 0.1, minimum depth for initial random organisms 2, maximum depth for initial random organisms 6, maximum depth of mutation fragment 6, and maximum permissible depth of organisms after crossover 17. The

generative method for the initial random population was *ramped half-and-half*. The method of selection was tournament selection with a group size of 7. For the purpose of this research 100 independent genetic programming runs were executed. Only the results of the best runs (i.e., the models with the smallest error between the measurements and predictions) are presented in the paper.

### 3.1. Materials and porosity measurements

Our experiments involved woven fabrics made from staple yarns with two restrictions: first, only fabrics made from 100% cotton yarns (made by a combing and carding procedure on a ring spinning machine) were used in this research; second, fabrics were measured in the grey state to eliminate the influence of finishing processes. We believe that it is very hard, perhaps even impossible, to include all woven fabrics types to predict individual macro-porosity parameters precisely enough, and so we focused our research on unfinished staple yarn cotton fabrics. We would like to show that genetic programming can be used to establish the many relations between woven fabric constructional parameters and particular fabric properties, and that the results are more useful for fabric engineering than ideal theoretical models. The cotton fabrics varied according to yarn fineness (14 tex, 25 tex, and 36 tex), weave type (weave value), fabric tightness (55% - 65%, 65% - 75%, 75% - 85%), and denting. The constructional parameters of woven fabric samples are collected in Table 1. They were woven on a Picanol weaving machine under the same technological conditions. The weave values of plain (0.904), twill (1.188), and satin (1.379) fabrics, as well as fabric tightness, were determined according to Kienbaum's setting theory [36].

We used an optical method to measure porosity parameters of woven fabrics, since it is the most accurate technique for macro-pores with diameters of more than 10  $\mu\text{m}$ . For each fabric specimen, we observed between 50 and 100 macro-pores using a Nikon SMZ-2T computer-aided stereomicroscope with special software. We measured the following macro-porosity parameters: area of macro-pore cross-section, pore density, and equivalent macro-pore diameters.

### 3.2. Predictive models of woven fabric porosity parameters

Equations 29 and 30 present predictive models of the area of macro-pore cross-section  $A_p$  and macro-pore density  $N_p$ , respectively [37]. Here  $V$  is the weave factor,  $T$  is the yarn linear density in tex,  $t$  is the fabric tightness in %, and  $D$  is the denting in ends per reed dent. The open porosity and equivalent diameter are calculated using Equations 17 and 19, respectively, where for  $A_p$  and  $N_p$  the predicted values are taken into account. Because the model of the area of macro-pore cross-section is more complex, the functions  $f_1, f_2, \dots, f_{10}$  are not presented here but are written in the appendix. When calculating the values of models, the following rules have to be taken into account: the protected division function returns to 1 if denominator is 0; otherwise, it returns to the normal quotient. The protected power function raises the absolute value of the first argument to the power specified by its second argument.

By a comparison of both GA models (Equations 29 and 30) with the theoretical ones (Equations 11-13 and 14), the complexity of GA models is obvious and derives from the factors involved in the models. Namely, factors involved in GA models don't ignore the irregularity of macro-pores cross-section area as well as the number of pores, due to the phenomenon of latticed pores in the case of staple yarns (which depends on the type of weave – factor V and fabric tightness – factor t) and the phenomenon of thread spacing irregularity (factor D), as theoretical models do. Theoretical model for the macro-pore cross-section area assumes that all macro-pores in woven structure have the same cross-section area regardless the type of used yarns, type of weave, fabric tightness and denting, whilst the theoretical model for the pore density assumes no reduction of the number of pores.

Ref.	Yarn linear density <i>T</i> , tex	Weave value <i>V</i>	Fabric tightness <i>t</i> , %	Denting <i>D</i> , ends/reed dent
1	14	0.904	62	2
2	14	0.904	70	2
3	14	0.904	84	2
4	14	1.188	62	3
5	14	1.188	70	3
6	14	1.188	80	3
7	14	1.379	59	5
8	14	1.379	69	5
9	14	1.379	79	5
10	25	0.904	62	2
11	25	0.904	73	2
12	25	0.904	83	2
13	25	1.188	63	2
14	25	1.188	73	2
15	25	1.188	84	2
16	25	1.379	60	2+3
17	25	1.379	70	2+3
18	25	1.379	81	2+3
19	36	0.904	62	1
20	36	0.904	71	1
21	36	0.904	83	1
22	36	1.188	63	2
23	36	1.188	72	2
24	36	1.188	83	2
25	36	1.379	58	2+3
26	36	1.379	65	2+3
27	36	1.379	79	2+3

**Table 1.** The constructional parameters of woven fabric samples

$$A_p = \frac{1}{V^2 t^2} \left( f_1 + \frac{t}{f_2 - f_3} \right) \cdot \left( f_8 (f_9 + f_{10}) + TV \left( f_4 + f_7 + \frac{f_5 f_6}{t(T+t)} \right) \right) \quad (29)$$

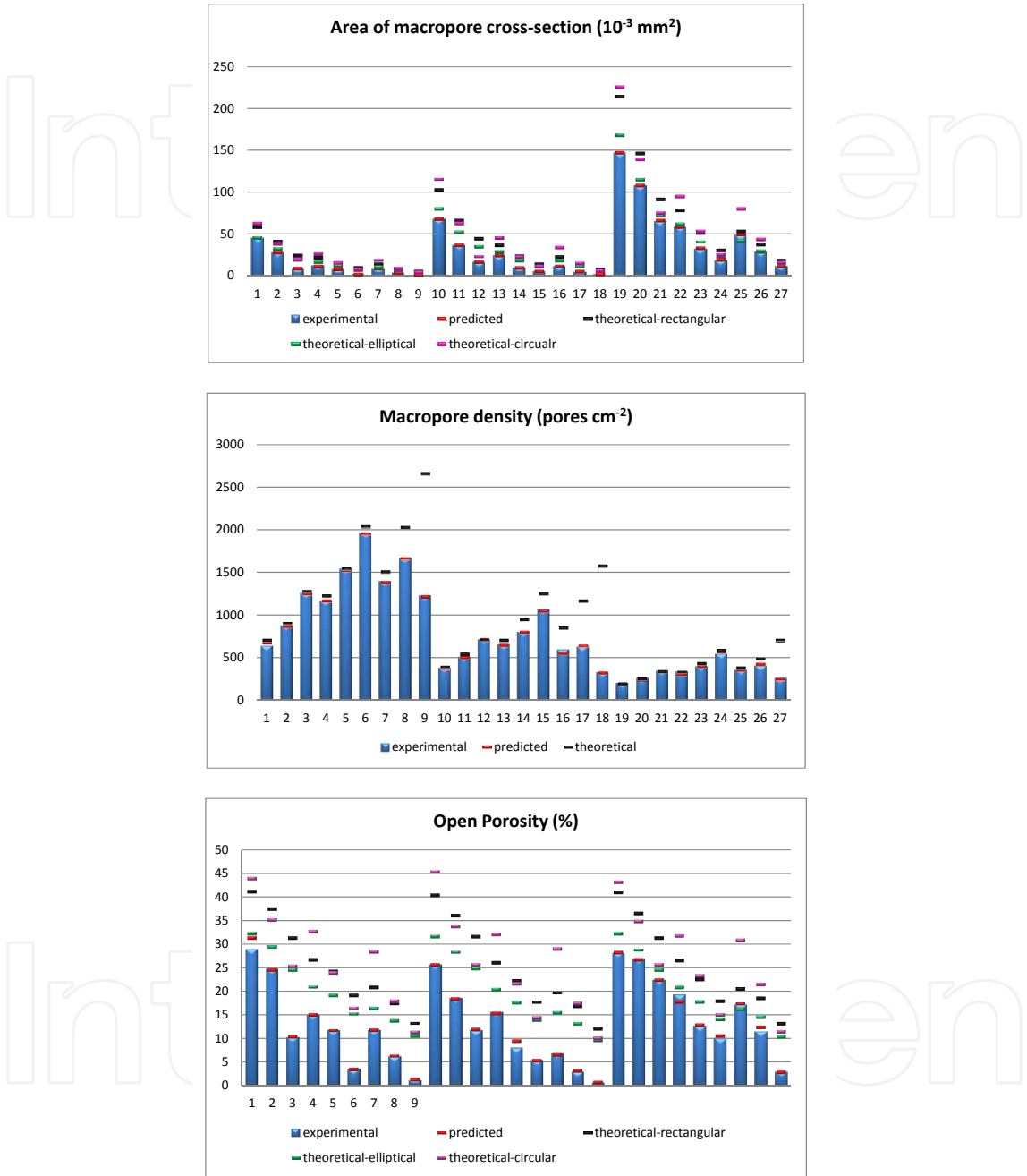
$$N_p = \frac{(D+V)(D+t) \left( t + \frac{9+t}{T-V} \right)}{2.93+T} - \frac{D \left( t + \left( T+V-t + \frac{Vt}{D} \right)^{-7} + \frac{-1.4+2D+0.95DV^{-1-T} + \frac{9+D+t}{-6.6+T}}{T + \frac{t}{D+V}} \right)}{(D+T) \left( 1.055 - 0.8816V + \frac{D}{V \sqrt{\frac{T}{V^D} - t}} \right)} - \frac{D \left( \frac{D \left( 1.05 - V - \frac{6.3}{(-1+D)DV^T} \right)}{DT-t} + \frac{t + \frac{T - \frac{t}{D}}{D+V^2}}{T + \frac{9.5+t}{D-T+V}} \right)}{1.055 - V + \frac{3.56 \cdot 5.18^V (D+T)}{V(1.05+V+Tt)}} \quad (30)$$

Figure 10 presents a comparison of the experimental, predicted, and theoretical values of macro-porosity parameters. Theoretical values of macro-pore density are calculated on the basis of an ideal model of porous structure using Equation 14. By calculation of the theoretical values of the area of macro-pore cross-section, open porosity, and the equivalent pore diameter, the circular, rectangular, and elliptical shape of macro-pore area are taken into account.

Theoretical values of woven fabric porosity parameters deviate from experimental ones on average by 118.3% (min 8.8%, max 452.9%) for the area of the macro-pore with rectangular cross-section, 111.5% (min 14.5%, max 370.6%) for the area of the macro-pore with circular cross-section, 72.8% (min 0.2%, max 335.3%) for the area of the macro-pore with elliptical cross-section, 37.3% (min 0.0%, max 395.0%) for the macro-pore density, 232.6% (min 19.9%, max 1900.1%) for the open porosity of fabrics with rectangular pore cross-section, 221.0% (min 14.3%, max 1558.0%) for the open porosity of fabrics with circular pore cross-section, 166.3% (min 5.9%, max 1479.0%) for the open porosity of fabrics with elliptical pore cross-section, 43.7% (min 4.3%, max 135.1%) for the equivalent pore diameter where rectangular pore cross-section is taken into account, 43.7% (min 7.0%, max 116.9%) for the equivalent pore diameter where circular cross-section is taken into account, and 28.0% (min 0.1%, max 108.6%) for the equivalent pore diameter where elliptical pore cross-section is taken into account.

The results of woven fabric porosity parameters determined with models based on genetic programming show very good agreement with experimental values (Figure 11) and justify the complexity of GA models. The predicted values deviate from experimental ones on average by 1.5% (min 0.0%, max 10.2%) for the area of the macro-pore cross-section, 2.0% (min 0.0%, max 8.0%) for the macro-pore density, 3.2% (min 0.0%, max 10.1%) for the open porosity, and 0.8% (min 0.0%, max 5.2%) for the equivalent macro-pore diameter. The

correlation coefficients between the predicted and experimental values are 0.9999, 0.9989, 0.9941, and 0.9997 for the area of macro-pore cross-section, macro-pore density, open porosity, and equivalent diameter, respectively.



**Figure 10.** Results of woven fabric porosity parameters

The models are based on image analysis technique and assumption that woven samples are transparent. The boundary limits for the validity of the models are as follows: 1. the minimal values for yarn linear density, weave factor and fabric tightness, are 14 tex, 0.904, and 55%, respectively, 2. the maximal values for yarn linear density, weave factor and fabric tightness are 36 tex, 1.379, and 85%, respectively.

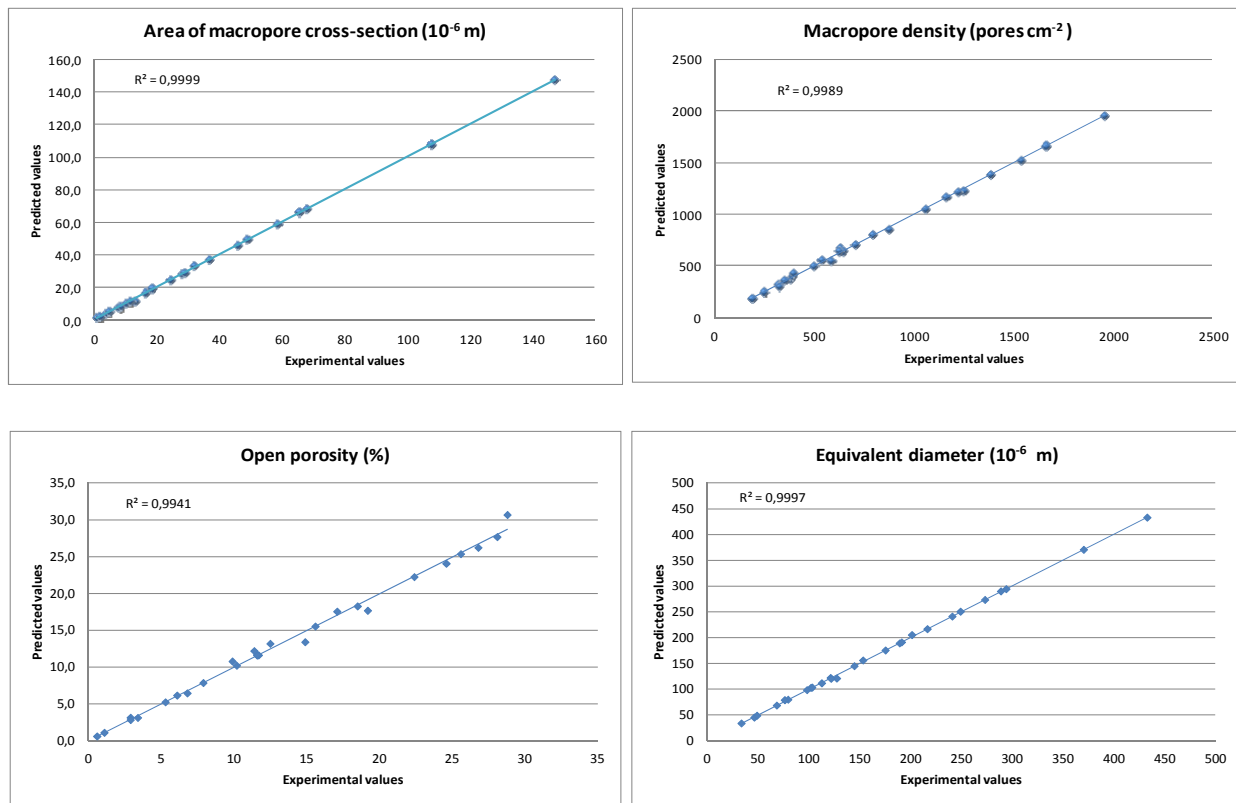


Figure 11. Scatter plots of experimental and predicted porosity parameters using GP models

#### 4. The usage of genetic algorithm to predict nonwoven fabric porosity parameters

In this research, the genetic algorithm was used for definition of predictive models of nonwoven fabric porosity parameters. Since needle-punched nonwoven fabrics have completely different porous structure when compared to woven fabrics, it is inappropriate to focus on open porosity through the prediction of the area of macro-pore cross-section and macro-pore density. The most valuable porosity parameters for needle-punched nonwoven porous structure characterisations are total porosity and mean pore diameter, and those parameters were the subjects of our research. Since the basic steps in evolutionary computation are well-known, only a brief description follows. Firstly, the initial population  $P(t)$  of the random organisms (solutions) is generated. The variable  $t$  represents the generation time. The next step is the evaluation of population  $P(t)$  according to the fitness measure. Altering the population  $P(t)$  by genetic operations follows. The genetic operations alter one or more parental organism(s); thus, creating their offspring. The evaluation and alteration of population takes place until the termination criterion has been fulfilled. This can be the specified maximum number of generations or a sufficient quality of solutions [38]. More comprehensive information on evolutionary computation can be found in [39].

The independent input variables were fibre fineness -  $T$  (dtex), nonwoven fabric area mass -  $m$  ( $\text{g}/\text{m}^2$ ), and nonwoven fabric thickness -  $D$  (mm). The dependent output variables were mean pore diameter  $d_p$  ( $\mu\text{m}$ ) and total porosity  $\varepsilon$  (%). Since the GA approach is unsuitable for the

evolution of prediction models (organisms) in their symbolic forms, it is necessary to define them in advance [38]. In this study, a quadratic polynomial equation with three variables was used as a prespecified model for the prediction of porosity parameters as follows:

$$Y = c_1 + c_2m + c_3D + c_4T + c_5m^2 + c_6D^2 + c_7T^2 + c_8mD + c_9mT + c_{10}DT + c_{11}mDT \quad (31)$$

where,  $Y$  is the dependent output variable,  $m$  is the nonwoven fabric mass per unit area in  $\text{g/m}^2$ ,  $D$  is the nonwoven fabric thickness in mm,  $T$  is the fibre fineness in dtex, and  $c_1 \dots c_{11}$  are constants. The main reasons for this selection were as follows: 1. a polynomial model is relatively simple, 2. for the problem studied we did not expect harmonic dependence of the output variables, 3. some preliminary modelling-runs with different types of prespecified models showed that the quadratic polynomial model provides very good selection in terms of prediction quality. In our research, the initial random population  $P(t)$  consisted of  $N$  prespecified models (Equation 31) where  $N$  is the population size. Of course, in our computer implementation of the GA, the population  $P(t)$  consisted only of the  $N$  sets of the real-valued vectors of model constants. The individual vector is equal to:

$$c = (c_1, c_2, \dots, c_{11}) \quad (32)$$

The absolute deviation  $D(i,t)$  of individual model  $i$  (organism) in generation time  $t$  was introduced as a fitness measure. It was defined as:

$$D(i,t) = \sum_{j=1}^n |E(j) - P(i,j)| \quad (33)$$

where,  $E(j)$  is the experimental value for measurement  $j$ ,  $P(i, j)$  is the predicted value returned by the individual model  $i$  for measurement  $j$ , and  $n$  is the maximum number of measurements. The goal of the optimisation task was to find such a predictive model (defined by Equation 31), that Equation 33 would give as low an absolute deviation as possible. Therefore, the aim was to find out appropriate real-valued constants in Equation 32. However, since it was unnecessary that the smallest values of the above equation also meant the smallest percentage deviation of this model, the average absolute percentage deviation of all measurements for individual model  $i$  was defined as:

$$\Delta(i) = \frac{D(i,t)}{|E(j)|n} \cdot 100\% \quad (34)$$

The Equation 33 was not used as a fitness measure for evaluating population, but only for finding the best organism within the population, after completing the run.

The altering of population  $P(t)$  was effected by reproduction, crossover, and mutation. For the crossover operation, two parental vectors, e.g.,  $c_1$  and  $c_2$  were randomly selected. Then the crossover took place between two randomly-selected parental genes having the same index. Two offspring genes were created according to the extended intermediate crossover, as considered by Mühlenbeim and Schlierkamp-Voosen [40]. During the mutation

operation, one parental vector  $c$  was randomly selected. Then, the mutation took place in one randomly selected parental gene. During both the crossover and mutation processes, the numbers of crossover and mutational operations performed on parental vector(s), were randomly selected. The evolutionary parameters for modelling by genetic algorithms were: population size 300, maximum number of generations to be run 5000, probability of reproduction 0.1, probability of crossover 0.8 and probability of mutation 0.1. Tournament selection with a group size of 5 was used. For the purpose of the research 200 independent genetic algorithms runs were carried out. Only the best models are presented in the paper.

#### 4.1. Materials and porosity measurements

Bearing in mind the fact that nonwovens have very different structures and, thus, also porosity parameters due to their sequences when web-forming, bonding, as well as finishing methods, the nonwoven fabric samples were limited to one type of nonwoven fabrics – those needle-punched nonwoven fabrics made from a mixture of polyester and viscose staple fibres. Nonwoven multi-layered webs were first obtained from the same manufacturing process by subjecting the fibre mixtures to carding and then orienting the carded webs in a cross-direction by using a cross lapper to achieve web surface mass ranges of 100-150, 150-200, 250-300, and 300-350 g/m<sup>2</sup>, and a web volume mass range of 0.019-0.035 g/cm<sup>3</sup>. The webs were made from a mixture of polyester (PES) and viscose (VIS) staple fibres of different content, fineness, and lengths, as follows: samples 1–3 from a mixture of 87% VIS fibres (1.7 dtex linear density, 38 mm length) and 12.5% of PES fibres (4.4 dtex linear density, 50 mm length), samples 4–7 from a mixture of 60% VIS fibres (1.7 dtex linear density, 38 mm length) and 40% PES fibres (3.3 dtex linear density, 60 mm length), samples 8–11 from a mixture of 30% VIS fibres (3.3 dtex linear density, 50 mm length), 40% PES fibres type 1 (6.7 dtex linear density, 60 mm length) and 30% of PES fibres type 2 (4.4 dtex linear density, 50 mm length), samples 12–15 from a mixture of 70% PES fibres type 1 and 30% PES type 2. Multi-layered carded webs were further subjected to pre-needling using needle-punching machine, under the following processing parameters of one-sided pre-needle punching: stroke frequency 250/min; delivery speed 1.5 m/min; needling density 30/cm, depth of needle penetration 15 mm, and felting needles of 15x18x38x3 M222 G3017. The processing parameters of further two-sided needle-punching were as follows: stroke frequency 900/min; delivery speed 5.5 m/min; needling density 60/cm (30/cm upper and 30/cm lower), depth of upper and lower needle penetrations 12 mm, and felting needles of 15x18x32x3 M222 G3017. The webs were further processed through a pair of heated calendars at under 180 °C with different gaps between the rollers, in order to achieve further changes in fabric density and, consequently, in the porosity within the range of 80–92 %. The constructional parameters of the nonwoven fabric samples are collected in Table 2. All the nonwoven fabric samples were in a grey state to eliminate the influence of finishing treatments. The constructional parameters of the nonwoven fabric samples, e.g. the nonwoven fabric mass per unit area and thickness were measured according to ISO 9073-1 (Textiles – Test Methods for nonwovens – Part 1: Determination of mass per unit area) and ISO 9073-2 (Textiles – Test Methods for nonwovens – Part 2: Determination of thickness).

Ref.	Average fibre fineness <i>T</i> , dtex	Fabric mass per unit area <i>m</i> , g/m <sup>2</sup>	Fabric thickness <i>D</i> , mm
1	2.0	143	1.202
2	2.0	142	0.941
3	2.0	142	0.576
4	2.3	173	1.509
5	2.3	201	1.558
6	2.3	171	0.941
7	2.3	200	1.071
8	5.0	259	1.360
9	5.0	259	1.261
10	5.0	279	1.182
11	5.0	274	1.112
12	6.0	298	1.400
13	6.0	304	1.266
14	6.0	352	1.347
15	6.0	343	1.235

**Table 2.** The constructional parameters of nonwoven fabric samples

The porosity parameters of the nonwoven fabric samples were measured using the Pascal 140 computer aided mercury intrusion porosimeter, which measures pores' diameters between 3.8 - 120  $\mu\text{m}$ , and operates under low pressure. The mercury intrusion technique is based on the principle that non-wetting liquid (mercury) coming in contact with a solid porous material can not be spontaneously absorbed by the pores of the solid itself because of the surface tension, but can be forced by applying external pressure. The required pressure depends on the pore-size and this relationship is commonly known as the Washburn equation [9]:

$$P = \frac{-2 \cdot \gamma \cdot \cos \theta}{r} \quad (35)$$

where,  $P$  is the applied pressure,  $\gamma$  is the surface tension of mercury,  $\theta$  is the contact-angle and  $r$  is the capillary radius. The distribution of pore size, as well as the total porosity and the specific pore volume can be obtained from the relationship between the pressure necessary for penetration (the pore dimension) and the volume of the penetrated mercury (pore volume). There are certain main assumptions necessary when applying the Washburn equation: the pores are assumed to be of cylindrical shape and the sample is pressure stable.

Each nonwoven sample of known weight was placed in the dilatometer, then the air around the sample was evacuated and finally the dilatometer was filled with mercury by increasing the pressure up to the reference level. The volume and pressure measurements' data were transferred into the computer programme and the following data were detectable or calculated: the specific pore volume ( $\text{mm}^3/\text{g}$ ), the average pore diameter ( $\mu\text{m}$ ) and the total

porosity (%). The volume of penetrated mercury is directly the measure of the sample's pore volume expressed as a specific pore volume in mm<sup>3</sup>/g, and is obtained by means of a capacitive reading system. The average pore diameter is evaluated at 50% of the cumulative volume of mercury.

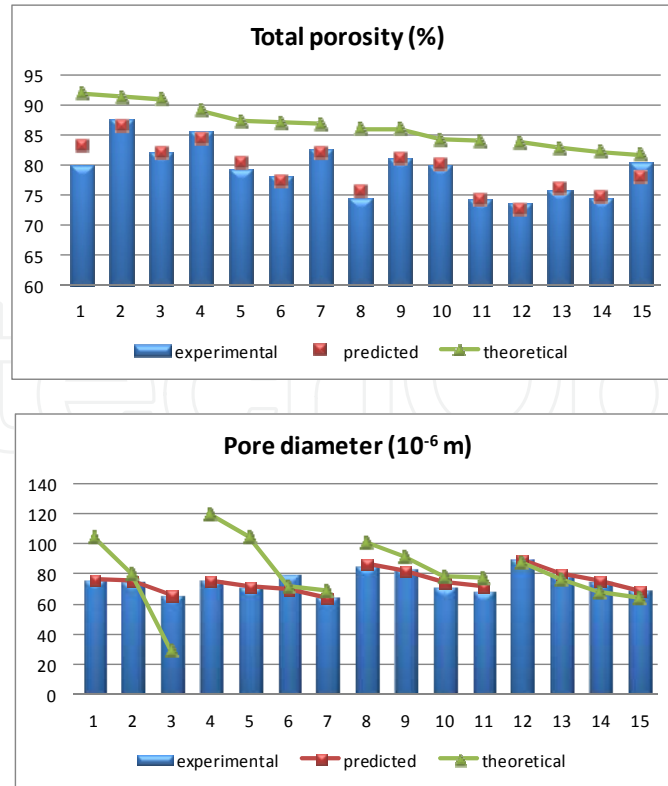
#### 4.2. Predictive models of nonwoven fabric porosity parameters

Equations 36 and 37 present predictive models of the total porosity  $\varepsilon$  and mean pore diameter  $d_p$ , respectively. Here  $T$  is the fibre fineness in dtex,  $m$  is the nonwoven fabric mass per unit area in g/m<sup>2</sup>, and  $D$  is the nonwoven fabric thickness in mm.

$$\begin{aligned} \varepsilon = & 150.1 - 8.61 \cdot 10^{-2} m + 3.21 \cdot 10^{-2} D - 66.04 \cdot T - 1.09 \cdot 10^{-3} m^2 - 28.74 \cdot D^2 + \\ & + 0.89 \cdot T^2 + 0.24 \cdot m \cdot D + 0.20 \cdot m \cdot T + 32.16 \cdot D \cdot T - 0.10 \cdot m \cdot D \cdot T \end{aligned} \quad (36)$$

$$\begin{aligned} d_p = & 103.12 - 0.39 \cdot m + 6.01 \cdot D - 0.73 \cdot T - 2.12 \cdot 10^{-3} m^2 - 30.77 \cdot D^2 - 3.79 \cdot T^2 + \\ & + 0.46 \cdot m \cdot D + 0.16 \cdot m \cdot t + 1.13 \cdot D \cdot T - 3.79 \cdot 10^{-3} \cdot m \cdot D \cdot T \end{aligned} \quad (37)$$

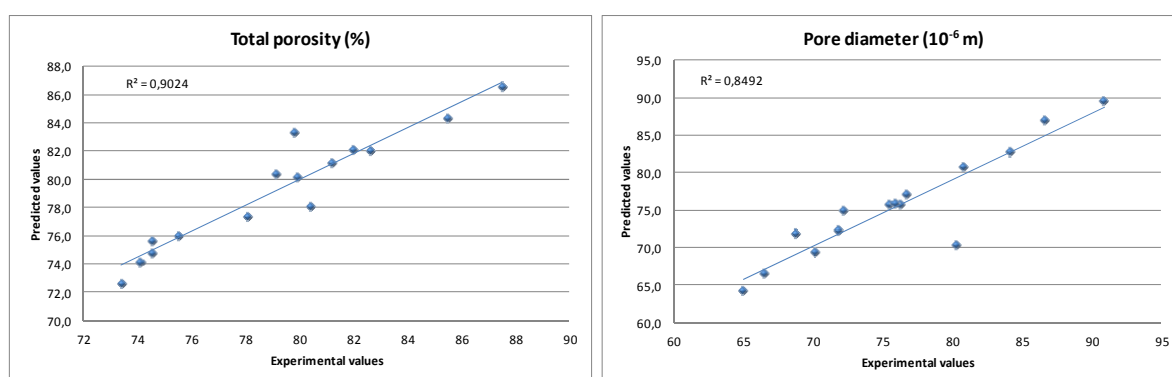
Figure 12 presents a comparison of the experimental, predicted and theoretical values of porosity parameters, e.g. total porosity and mean pore diameter. The theoretical values of total porosity and mean pore diameters were calculated using Equation 22 and 27-28, respectively.



**Figure 12.** Results of nonwoven fabric porosity parameters

In Figure 12, the theoretical values of total porosity and mean pore diameter as well as predicted values of pore diameter are linked with lines while samples (1-3, 4-7, 8-11, and 12-15) are arranged regarding their decreased porosity. The results show that nonwovens with similar porous structure and lower porosity also have lower pore diameter. The experimental values of total porosity are for some samples not in a good agreement with theoretical ones, while samples which should have the highest porosity actually have the lowest (samples No. 1, 8, and 12). The reason may lie in fact, that these samples contain more closed pores which are not detectable with mercury porosimetry.

The results show that the theoretical values of porosity parameters deviate from experimental ones on average by 8.0% (min 0.0%, max 15.4%) for total porosity and by 19.7% (min 2.9, max 57.3%) for pore diameter, whilst the predicted values, calculated using Equations 36-37, are in better agreement with the experimental ones. The mean predicted error is: 1.1% (from 0.0% to 4.4%) for the total porosity and 1.9% (from 0.0% to 12.4%) for the average pore diameter. The correlation coefficients between the predicted and experimental values are 0.9024 and 0.8492 for the total porosity and the average pore diameter, respectively. Scatter plots of the experimental and predicted values for porosity parameters, are depicted in Figure 13.



**Figure 13.** Scatter plots of experimental and predicted porosity parameters using GA models

## 5. Conclusion

By a new fabric developing, there is a need to know some relationships between the constructional parameters of fabrics and their predetermined end-usage properties in order to produce fabrics with desired quality. Fabric constructors develop a new fabric construction on the basis of their experiences or predictive models using different modelling tools of which deterministic and nondeterministic are distinguished. In general, the models obtained by deterministic modelling tools are the results of strict mathematical rules while in the case of models obtained by nondeterministic modelling tools, there are no precise, strict mathematical rules. Our study focused on the development of predictive models based on the genetic methods, e.g. genetic programming and genetic algorithms, in order to predict some porosity parameters of woven and nonwoven fabrics. Predictive models of the:

1. area of macro-pore cross-section and macro-pore density of woven fabrics based on the constructional parameters of woven fabrics (yarn linear density, weave factor, fabric

tightness, denting), image analysis as testing method of porosity measurements, and genetic programming, and 2. total porosity and mean pore diameter of nonwoven fabrics based on the constructional parameters of nonwoven fabrics (fibre linear density, fabric mass per unit area, fabric thickness), mercury intrusion porosimetry as testing method of porosity measurements, and genetic algorithm, were developed. Open porosity and equivalent pore diameter of woven fabric were also predicted using values calculated on the basis of predictive models of the area of macro-pore cross-section and pore density, and known mathematical relationships. All proposed predictive models were created very precisely and could serve as guidelines for woven/nonwoven engineering in order to develop fabrics with the desired porosity parameters.

In general, for prediction of porosity parameters of woven or nonwoven samples both modelling tools can be used, e.g. GA and GP. Usually, GP method is used for more difficult problems. Our purpose was to show usability and effectiveness of both methods. By woven fabric modelling, the range of porosity parameters' measurements was substantial larger with more input variables when compared to the nonwoven fabrics (and this means more difficult problem), so the GP was used as modelling tool. By GP modelling, the models are developed in their symbolic forms, thus more precise models are developed in regard to the GA modelling, where only coefficients of prespecified models are defined. At the same time, for GP modelling more measurements data are desired for better model accuracy, while by GA modelling good results are achieved by lower number of measurements (in our case 27 measurements were available for woven fabrics and only 15 for nonwoven fabrics). The advantage of GP modelling is its excellent prediction accuracy, while its disadvantage is the complexity of the developed models. In general, by GA modelling, the developed models are simple but less accurate.

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## Appendix

$$f_1 = 12.856 + \frac{T}{V} + \frac{T}{Dt} \times \left( 35.3 + D + \frac{6.43}{2D + \frac{2T^2}{Vt} - \frac{t}{D + \frac{4.74T^3}{t^2} + \frac{T(T-D)}{t}}} \right),$$

$$f_2 = -12.856 - D + T - \frac{2T^2}{Vt} + \frac{0.0727 \cdot V \cdot t^2}{T^2}$$

$$f_3 = T \left( \frac{7V}{T - 28.86V} + \frac{35.3 + D + \frac{0.5t}{T}}{V} + \frac{t}{\left( T - \frac{4.1739T}{V} + t \right) \left( D - \frac{4.1739T}{V} + t + \frac{0.5t}{T} \right)} \right)^{-1},$$

$$f_4 = 19.3 + 0.034 \left( 6.43 + T + \frac{2T^2}{V^2t} \right) + \frac{2T^2}{Vt} - \frac{(28.86 - 2.37T - t)}{7.43 + D - 4.1739T + t + \frac{(T^2 + Dt)}{Vt}},$$

$$f_5 = T \left( \frac{T}{t} - 2.37 \right) \left( 77 + 4D + \frac{D + \frac{2(35.3 - D)T \left( 35.3 + T + \frac{T}{V} \right)}{t^2}}{28.86 + T - \frac{4.1739T}{V} + V + t} \right), f_6 = \frac{V^2t^2}{3.3T^2 + 28.86Vt - 0.98TVt} - T$$

$$f_7 = \frac{\frac{2T^2}{Vt} - \frac{t^3}{T^2(2T + t) + D(Tt - 2T^2 + t^2)}}{77 + 2D - Vt},$$

$$f_8 = 41.7137 + 2D + \frac{35.3 + D - \frac{4.1739T}{T^2 - 8.393t}}{V} + \frac{t}{35.3 + \frac{T}{V} - \frac{6.88T^2(35.3 + T)}{DVt^2} + t},$$

$$f_9 = \frac{35.3 + D}{V} + \left( \frac{35.3 + D + \frac{\frac{28.86}{V} + t + \frac{(T + t)(T - 0.29Vt)}{V^2t}}{T - \frac{4.1739T}{V} + t}}{6.43 + \frac{28.86T}{DV} - \frac{8.35(35.29 + 2D)T}{t}} \right)$$

$$f_{10} = \frac{28.86 + t + \frac{(28.86 - D)t - T^2}{\frac{2T^2}{V^2} - \frac{99.2Vt}{T} + t} \left( 6.43 + \frac{Vt}{T - 0.24D} \left( D - \frac{4.1739T}{V} + 0.034TV + t \right) \right)}{41.7137 + D - \frac{16.786T^3}{DVt^2} - \frac{8.393T^2}{V^2t} + \frac{Vt^2}{T(2.37T + t(V - 8.393))}}$$

## 6. References

- [1] M. Brezočnik, *The Usage of Genetic Programming in Intelligent Manufacturing Systems*, Maribor: University of Maribor, Faculty of Mechanical Engineering, 2000.
- [2] J.R. Koza, *Genetic programming II*, Massachusetts: The MIT Press, 1994.
- [3] J.R. Koza, *Genetic programming III*, San Francisco: Morgan Kaufmann, CA, 1999.
- [4] M. Brezocnik, J. Balic, "Emergence of intelligence in next-generation manufacturing systems", *Robot. Comput. Integrat. Manufact.*, Vol. 19, pp. 55-63, 2003.
- [5] P. Udhayakumar and S. Kumanan, "Task Scheduling of AGV in FMS Using Non-Traditional Optimization Techniques", *Int. Journal of Simulation Modelling*, Vol. 9, pp. 28-39, 2010.
- [6] N. Chakraborti, R. Sreevathsan, R. Jayakanth and B. Bhattacharya, "Tailor-made material design: An evolutionary approach using multi-objective genetic algorithms", *Computational Materials Science*, Vol. 45, pp. 1-7, 2009.
- [7] S. Mohanty, B. Mahanty and P.K.J. Mohapatra, "Optimization of hot rolled coil widths using a genetic algorithm", *Materials and Manufacturing Processes*, Vol. 18, pp. 447-462, 2003.
- [8] M. Brezočnik and J. Balič, »A Genetic-based Approach to Simulation of Self-Organizing Assembly«, *Robot. Comput. Integrat. Manufact.*, Vol. 17, pp. 113-120, 2001.
- [9] *Porosimeter Pascal Instruction Manual*, Milan: Thermo Electron S.p.A, 2004.
- [10] K. L. Hatch, *Textile Sciences*, New York: West Publishing Company, 2000.
- [11] P. Bajaj and A. Sengupta, »Protective Clothing«, in *Textile Progress*, Manchester, The Textile Institute, 1992, pp. 1-94.
- [12] Y. Shoshani and Y. Yakubov, »A Model for Calculating the Noise Absorption Capacity of Nonwoven Fiber Webs«, *Textile Research Journal*, Vol. 69, pp. 519-526, 1999.
- [13] M. Mohammadi and P. Banks-Lee, »Determining Effective Thermal Conductivity of Multilayered Nonwoven Fabrics«, *Textile Research Journal*, Vol. 73, pp. 802-808, 2003.
- [14] N. Pan and P. Gibson, *Thermal and moisture transport in fibrous materials*, Cambridge: Woodhead Publishing Limited and CRC Press LLC, 2006.
- [15] K. Dimitrovski, *New Method for Assessment of Porosity in Textiles*, Doctoral Dissertation, Ljubljana: University of Ljubljana, Textile Department, 1996.
- [16] B. Neckar and S. Ibrahim, »Theoretical Approach for Determining Pore Characteristics Between Fibres«, *Textile Research Journal*, Vol. 73, pp. 611-619, 2003.
- [17] G. Lombard, A. Rollin and C. Wolff, »Theoretical and Experimental Opening Sizes of Heat-Bonded Geotextiles«, *Textile Research Journal*, Vol. 59, pp. 208-217, 1989.
- [18] M. J. Park, S. H. Kim, S. J. Kim, S. H. Jeong and J. Jaung, »Effect of Splitting and Finishing on Absorption/Adsorption Properties of Split Polyester Microfiber Fabrics«, *Textile Research Journal*, Vol. 71, pp. 831-840, 2001.
- [19] K. Kaneko, »Determination of pore size and pore size distribution«, *Journal of Membrane Science*, Vol. 96, pp. 59-89, 1994.
- [20] A. Jena and K. Gupta, »Liquid Extrusion Techniques for Pore Structure Evaluation of Nonwovens«, *International Nonwoven Journal*, Vol. 12, pp. 45-53, 2003.
- [21] B. Xu, »Measurement of Pore Characteristics in Nonwoven Fabrics Using Image Analysis«, *Clothing and Textiles Research Journal*, Vol. 14, pp. 81-88, 1996.

- [22] Y. L. Hsieh, »Liquid Transport in Fabric Structures«, *Textile Research Journal*, Vol. 65, pp. 299-307, 1995.
- [23] D. Jakšić and N. Jakšić, »Assessment of Porosity of Flat Textile Fabrics«, *Textile Research Journal*, Vol. 77, pp. 105-110, 2007.
- [24] V. Nagy and L. M. Vas, »Pore Characteristic Determination with Mercury Porosimetry in Polyester Staple Yarns«, *Fibres & Textiles in Eastern Europe*, Vol. 13, pp. 21-26, 2005.
- [25] D. Jakšić, The Development of the New Method to Determine the Pore Size and Pore Size Distribution in Textile Products, Ljubljana: Faculty of Natural Sciences and Technology, Department of Textile Technology, 1975.
- [26] P. D. Dubrovski, The Influence of Woven Fabric Geometry on Porosity of Biaxial Fabrics, Doctoral Dissertation, Maribor: University of Maribor, Faculty of Mechanical Engineering, 1999.
- [27] P. D. Dubrovski, »Volume Porosity of Woven Fabrics«, *Textile Research Journal*, Vol. 70, pp. 915-919, 2000.
- [28] P. D. Dubrovski, »A Geometrical Method to Predict the Macroporosity of Woven Fabrics«, *Journal of the Textile Institute*, Vol. 92, pp. 288-298, 2001.
- [29] A. V. Kulichenko and L. Langenhove, »The Resistance to Flow Transmission of Porous Materials«, *Journal of the Textile Institute*, Vol. 83, pp. 127-132, 1992.
- [30] J. C. Russ, The image Processing Handbook, CRC Press, 1996.
- [31] A. T. Purdy, Needle-punching, Manchester: The Textile Institute, 1980, pp. 49.
- [32] R. D. Anandjiwala and L. Boguslavsky, »Development of Needle-punched Nonwoven Fabrics from Flax Fibers for air Filtration Applications«, *Textile Research Journal*, Vol. 78, pp. 614-624, 2008.
- [33] J. Mao and S. J. Russell, »Modelling Permeability in Homogeneous Three-Dimensional Nonwoven Fabrics«, *Textile Research Journal*, Vol. 73, pp. 939-944, 2003.
- [34] X. Chen, F. Vroman, M. Lewandowski and A. Perwuelz, »Study of the Influence of Fiber Diameter and Fiber Blending on Liquid Absorption Inside Nonwoven Structures«, *Textile Research Journal*, Vol. 79, pp. 1364-1370, 2009.
- [35] A. Patanaik and R. Anandjiwala, »Some Studies on Water Permeability of Nonwoven Fabrics«, *Textile Research Journal*, Vol. 79, pp. 147-153, 2009.
- [36] M. Kienbaum, »Gewebegeometrie and Produktenwicklung«, *Melliand Textilberichte*, Vol. 71, pp. 737-742, 1990.
- [37] P. D. Dubrovski and M. Brezočnik, »Using Genetic Programming to predict the Macroporosity of Woven Cotton Fabrics«, *Textile Research Journal*, Vol. 72, pp. 187-194, 2002.
- [38] M. Brezočnik, M. Kovačič and L. Gusel, »Comparison Between Genetic Algorithm and Genetic Programming Approach for Modelling the Stress Distribution«, *Material and Manufacturing Processes*, Vol. 20, pp. 497-508, 2005.
- [39] T. Bäck, D. B. Fogel and Z. Michalewicz, Handbook of evolutionary computation, New York - Oxford: IOP Publishing and Oxford University Press, 1997.
- [40] M. Gen and R. Cheng, Genetic algorithms and engineering design, Canada: John Wiley & Sons, Inc., 1997.