Chapter

Modeling and Validating Analytic Relations for Electromagnetic Shielding Effectiveness of Fabrics with Conductive Yarns

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Abstract

Electromagnetic (EM) radiation may be harmful for human's health and for functioning of electronic equipment. The field of Electromagnetic Compatibility approaches various solutions to tackle this problem, while shielding of the radiation is one of the main solutions. Since the development of spinning technology for producing conductive yarns for fabrics, textile electromagnetic shields have become a valuable alternative to metallic shields. Their main advantages are given by the flexibility, the low weight and the good mechanical resistance, as well as by the possibility to precisely design the shield. The scientific literature includes several analytic relations for estimating the electromagnetic shielding effectiveness (EMSE), in case of woven fabrics with conductive yarns, which may be modeled as a grid of electric conductors. This book chapter tackles three different analytic models for estimating EMSE, which are useful to predict this functionality in the design phase of fabrics. The analytic relations are subsequently comparatively validated by EMSE measurements via TEM cell equipment of two woven fabrics with conductive yarns out of stainless steel and silver with a grid of 4 mm. Results of validated analytic relations are used for the approach of designing textile shields with regard to final application requirements.

Keywords: fabrics, yarns, stainless steel, silver, shielding effectiveness, modeling, validating

1. Introduction

Textile materials have reached in the last two decades a lot of additional functionalities in connection to new application fields [1]. Keywords such as technical textiles or smart textiles are increasingly gaining popularity among end users since various products are already available on the market. One important domain of technical textiles are fabrics destined for the construction sector – BUILDTECH, having electromagnetic (EM) shielding properties [2].

The research field of EM shielding fabrics combines at least two major disciplines, namely textile science and electromagnetic compatibility. As such, this chapter tackles interdisciplinary research with a lot of potential applications. In order to understand why EM shielding functionalities are relevant for textile materials, one has to consider the huge amount of EM radiation of our environment these days, caused by telecommunication or other electric energy sources [3].

Several studies prove that EM radiation is harmful for human beings [4]. Non-ionizing radiation produce a heating of the cellular tissues of the human body with negative impact on the health and may produce cancer [5]. Although the scientific studies have not done a strict correlation between radiation and deterioration of human's health, it is evident that a causality does exist [6].

Another problem are undesired radiation sources which cause interference with electronic devices. EM Interferences (EMI) are a deep topic of electromagnetic compatibility (EMC) science and one of the most applied solutions is shielding [7]. By shielding of interferences between electronic devices a proper functioning is ensured [8].

Shielding of EM radiation has been done traditionally by use of metallic plates. Due to their outstanding electric conductivity and the formation of Eddy currents, which produce an opposite EM field, the incident EM field is attenuated. The Shielding Effectiveness (EMSE) may be considered as basic quantity defining this attenuation. One of the most applied relation for measurement of EMSE is (1) [9]:

$$\begin{aligned} \boldsymbol{EMSE} &= \mathbf{10}\log_{10}\frac{\boldsymbol{Power\ of\ the\ incident\ field}}{\boldsymbol{Power\ of\ the\ transmitted\ field}} = \\ &= \boldsymbol{Reflection} + \boldsymbol{Absorption} + \boldsymbol{Multiple\ Reflections} \end{aligned} \quad (1)$$

However, although metallic plates have most effective EMSE properties due to their excellent electric conductivity properties, advanced technical textile materials are also used for such applications. The evolution of spinning technologies [10, 11] and the possibility to produce electric conductive fibers and yarns to be inserted into the fabrics structure, have made possible the manufacturing of textile electromagnetic shields. Either being inserted as yarns within the woven or knitted fabrics or as fibers within nonwoven fabrics, these novel textile materials render electric conductivity properties. The fabric structure with inserted conductive yarns may be designed according to weaving/knitting principles of textile science, having various yarn counts, fabric densities, weaves or float repeats [12].

When compared to metallic plates, electrical conductive textiles are flexible, lightweight and have a good mechanical resistance, and have as well the possibility to precisely design the shield for a certain application. Fabrics are currently preferred in many shielding applications over metallic plates, for the lower costs and the adaption in shape and size to the protected area. The insertion of conductive yarns into the fabric structure may yield various geometric patterns. One of the most common pattern is the grid pattern, which is obtained by inserting conductive yarns in warp and weft system of a woven fabric. Although such conductive woven fabrics do not reach the EMSE of metallic plates, they are used due to their special, mentioned properties.

Modeling of EMSE for electrical conductive materials was a task given by the necessity to estimate the material's properties in the design phase. Manufacturing EM shields without a prior estimation of their EMSE properties requires subsequent physical determinations and an ongoing loop of manufacturing and measurement. This undesired loop may be overcome by modeling of the desired property, in order to be able to estimate the property's values without manufacturing in view of the end application requirements. As such, important resources of time, materials, energy and men power are saved.

Modeling may be done by two main principles [13]:

- Phenomenological modeling: tackles the system as black box and uses experimental plans and statistics to get insight of experimental data;

- Mechanistic modeling: tackles the system as white box and describes by means of analytic relations their internal mechanism.

A simple mechanistic method to model the shielding effectiveness achieved through conductive plane shields was provided by Schelkunoff, and was named impedance method [7]. This method performs an analogy of the discontinuity of shield impedance with a lossy section within long bifilar transmission lines. The impedance method is considered to estimate sufficiently precise shielding effectiveness, by using following geometric and electric parameters: thickness of the shield, electric conductivity and magnetic permeability of the shield, over a specified frequency domain. Shielding is considered to occur due to three mechanisms: reflection loss of the wave due to mismatch of impedance between air and shield (electric conductivity and magnetic permeability are parameters with high sensitivity), absorption loss due to heat loss of the EM wave within the shield (thickness of shield is parameter with high sensitivity) and multiple reflection correction term due to re-reflection of the EM wave within the shield (1). In case of shields with grid structure such as the woven fabrics with conductive yarns, adaptations of the impedance method were accomplished, by introducing additional parameters of the fabric structure, such as the distance between conductive yarns or the conductive yarn's diameter. For modeling of EMSE by woven fabrics is a growing field of research, up-to-date contributions may be found in [14, 15]. A model based on the circuit method for near field electromagnetic waves was described in [16]. The circuit method was developed by Kaden and is considered next to the impedance method, main mechanistic model to estimate EMSE for electromagnetic shields, based on geometric and electric parameters [7].

This book chapter tackles modeling of EMSE for grid structures of woven fabrics with inserted conductive yarns, comparatively by mechanistic models of different analytic relations [17–20], with the purpose of being able to estimate EMSE in the design phase of the textile shielding products.

2. Materials and methods

This subchapter describes the analytic relations for estimation of the EMSE and the fabric samples with inserted conductive yarns and their properties, destined for validation.

2.1 Electric and geometric parameters for fabrics

Figure 1 presents the main geometric parameters of woven textile structures:

h - fabric thickness [m].

a - distance between conductive yarns (ratio between conductive and nonconductive yarns-float repeat) [m].

d – optical diameter of the conductive yarn [m].

The following electric parameters apply for the textile materials:

σ_y – Electric conductivity of the metallic yarns [S/m].

σ_f – Electric conductivity of the fabrics [S/m].

ε – Electric permittivity of the metallic yarns [F/m]

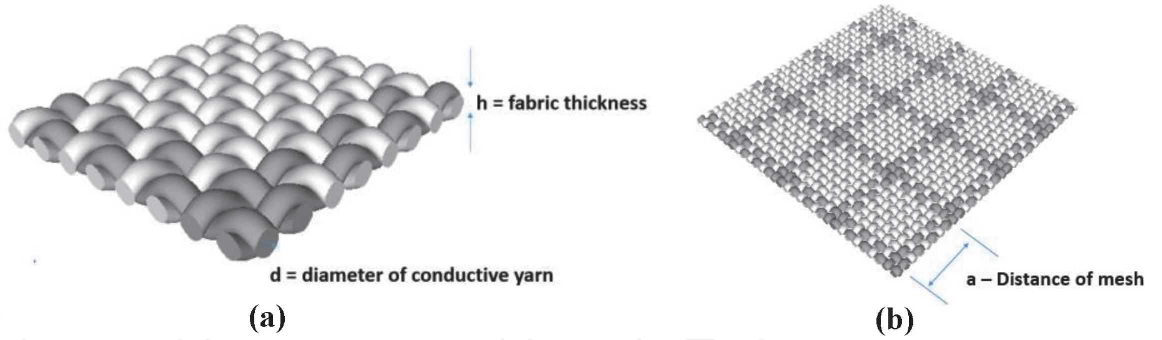


Figure 1.
(a) and (b) – Fabric structures and geometric parameters.

$\boldsymbol{\varepsilon = \varepsilon_0 \varepsilon_r}$, where:
ε_0 – Electric permittivity of vacuum $\varepsilon_0 = 1/(36\pi*10^9)$ F/m.
ε_r – Relative electric permittivity [1].
μ_y – Magnetic permeability of the metallic yarns [H/m].
μ_f – Magnetic permeability of the metallic fabrics [H/m]
$\boldsymbol{\mu = \mu_0 \mu_r}$, where:
μ_0 – Magnetic permeability of vacuum $\mu_0 = 4\pi*10^{-7}$ H/m.
μ_r – Relative magnetic permeability [1].
f – Frequency of electromagnetic (EM) field [Hz].
ω – Angular frequency of EM field $\boldsymbol{\omega = 2\pi f}$ [rad/s].
δ_y – Skin depth of the conductive yarn [m], expressed as:

$$\delta_y = \frac{1}{\sqrt{\pi f \mu_y \sigma_y}} \tag{2}$$

δ_f – Skin depth of the fabric [m], expressed as:

$$\delta_f = \frac{1}{\sqrt{\pi f \mu_f \sigma_f}} \tag{3}$$

2.2 Materials: the fabrics and their properties

Two types of fabrics with inserted conductive yarns made of stainless steel (F1) and silver (F2) were manufactured for validating the analytic relations of EMSE. The fabrics have similar structures, plain weave and a distance between conductive yarns of 5 mm, while F1 is based on stainless steel Bekinox BK50/2 yarns and F2 is based on silver Statex yarns. Cotton yarns of Nm50/2 were set as basic yarns. Both fabrics have been manufactured on rapier weaving looms, by inserting the conductive yarns in warp and weft system, with float repeat 6:2. **Table 1** presents their designed structure and their physical-mechanical and electric properties.

Figures 2 and **3** present pictures of the weaving loom and the warp beam at the company SC Majutex SRL (www.majutex.ro), used for manufacturing the textile woven fabrics F1 and F2.

* The electric conductivity of the yarns was computed considering the linear electric resistance of the yarns and the cross-section of the yarns, based on the measured optical diameter – relation (4).

		F1	F2
Conductive yarn (raw material / linear density)		Stainless steel and cotton spun yarn, Nm 50/2	Silver coated PA, 140x2 dtex
Linear electric resistance [Ω/m] R_l		3500	30
Electric conductivity yarns σ_y [S/m] *		7700	927000
Relative magnetic permeability yarns μr_y **		7.36	1
Basic yarn (raw material / linear density)		100% Cotton Nm 50/2	
Optical diameter yarn d [μm]		222	214
Weave		Plain weave	
Float repeat Basic: conductive yarn	Warp	6:2	6:2
	Weft	6:2	5:2
Fabric thickness h [mm]		0.55	0.49
Specific mass [g/m^2]		143	118
Fabric density [yarns/10 cm]	Warp	180	168
	Weft	170	150
Distance between conductive yarns a [mm]		5	5
Electric conductivity of fabrics σ_f [S/m] ***		41.54	589.0
Relative magnetic permeability of fabrics μr_f **		2.33	1

Table 1.
Textile structures and physical-mechanical & electric properties.

Figure 2.
Weaving loom.

$$\sigma_y = \frac{l}{R_l \cdot A} \tag{4}$$

Where:
σ_y – electric conductivity of the yarns [S/m].
R_l – linear electric resistance [Ω] for l = 1 m.
A – Cross-section of the yarn [m^2] with d optical diameter of yarn in **Table 1**.

** The relative magnetic permeability of the composite yarn respectively fabric was computed considering the relation presented in [21].

$$\mu_R = M_{de} MM_{de} \mu_{MM} \tag{5}$$

Where:
M_{de} - the equivalent percentage of bulk material from total volume;
MM_{de} – the equivalent percentage of the magnetic material from bulk material;
μ_{MM} – relative magnetic permeability of the magnetic material;
A relative magnetic permeability of stainless steel was set to μ_{MM} = 40, according to [22], while M_{de} and MM_{de} were computed according to the textile structure of yarn and fabric.

Ferromagnetic properties were computed for fabric F1 with inserted Bekinox stainless steel yarns, since fabric F2 with inserted Statex silver yarns has no ferromagnetic properties ($\mu_r \cong 1$).

The Bekinox BK50/2 stainless steel yarn is a spun yarn with 80% content of cotton fibers and 20% content of Bekinox VS stainless steel fibers, thus $MM_{de} = 0.20$.

For fabric F1, the cover factor of the woven fabric was considered for computing the parameter $M_{de} = 0.96$ (in one of our previous research studies [23]) and the ratio between conductive and basic yarns for computing the parameter $MM_{de} = 0.33$ (**Table 2**).

***The electric conductivity of fabrics was computed based on the measurement of the electric resistance of a piece of fabric (**Figure 4**) and relation (6).

The electric resistance R was measured via digital Ohmmeter and thickness h was measured via digital caliper for (6).

$$\sigma = \frac{1}{R} \cdot \frac{L}{l \cdot h} \tag{6}$$

Figure 3.
Warp beam.

μ_{MM} = 40 (stainless steel [23])	Stainless steel yarn	F1 fabric
M_{de}	100%	96%
MM_{de}	20%	33%
→Relative magnetic permeability μ_r	μ_{ry} 7.36	μ_{rf} = 2.33

Table 2.
Computation of relative magnetic permeability.

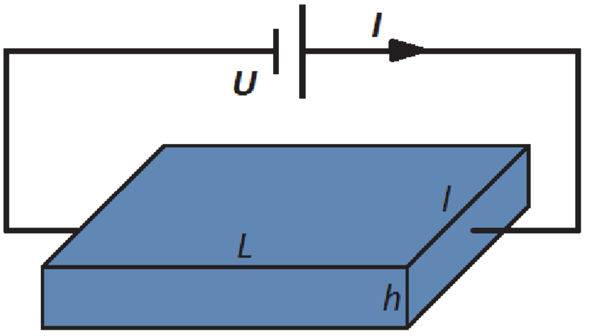


Figure 4.
Experimental setup for measurement of fabric's electric conductivity

2.3 Measured EMSE of the woven fabric samples

EMSE may be measured according to two main principles with following standardized methods:

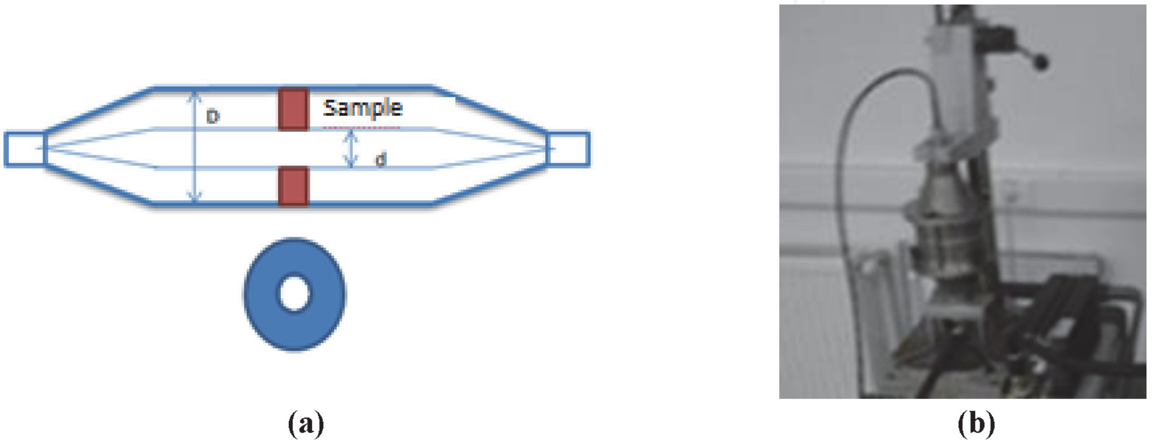
- Principle of TEM cell measurement system (standards ASTM ES-07 and ASTM D-4935);
- Principle of emitting and receiving antenna system (standards IEEE 299 and IEEE 299.1 – shielded enclosures with max length of 2 meter).

EMSE of both fabrics F1 and F2 was measured via a TEM cell measurement system, including signal generator, amplifier and oscilloscope, according to standard ASTM ES-07. **Figure 5a**) presents the scheme of a TEM cell and the washer-shaped textile sample, while **Figure 5b**) presents a picture of the TEM cell.

Figure 6 presents the diagram of EMSE to frequency on logarithmic scale with measured values for F1 and F2 in the frequency domain 0.1–1000 MHz.

The samples were coated on the edge with silver paint, in order to ensure a good electric conductivity at connection points to the TEM cell (**Figure 7**).

These experimental measurements of the fabrics with inserted conductive yarns of stainless steel (F1) and silver (F2), were done in order to validate two analytic relations for estimation of EMSE.



(a) **(b)**

Figure 5.
(a) and (b) TEM cell for EMSE measurement according to standard ASTM ES-07.

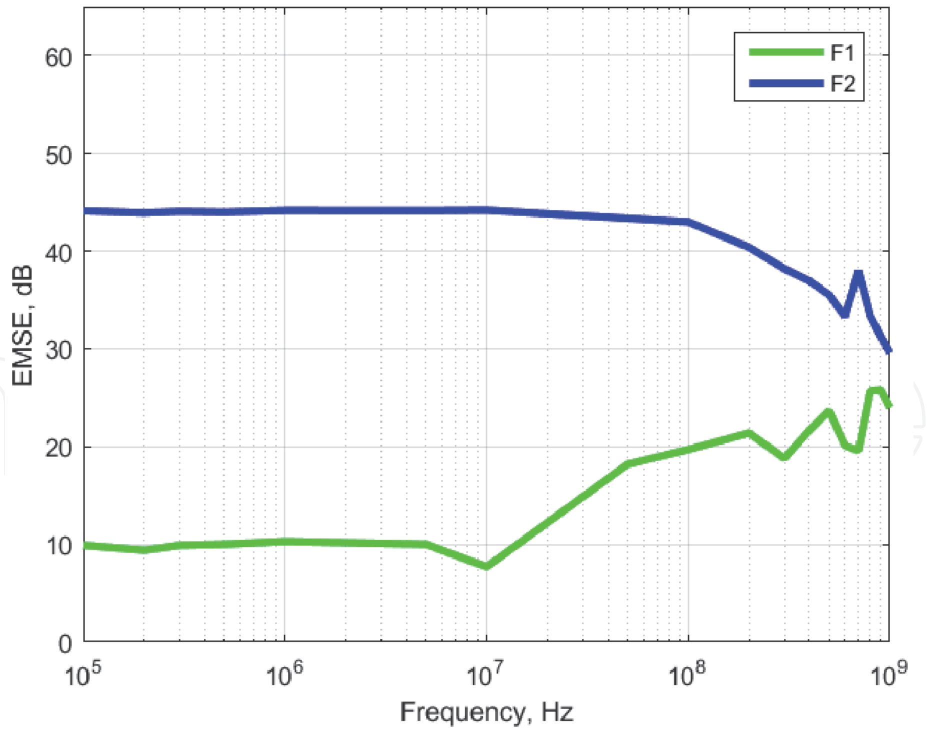


Figure 6.
EMSE measured for F1 and F2.

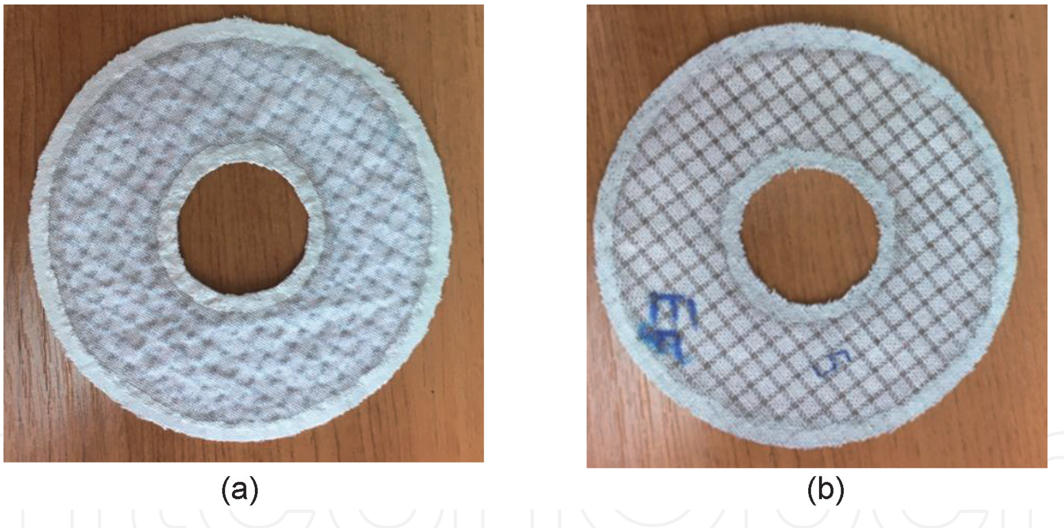


Figure 7.
(a) Sample F1 for TEM cell. (b) Sample F2 for TEM cell.

2.4 Methods: the analytic relations

The analytic relations of modeling EMSE are valid under certain physical premises:

- The incoming field is an electromagnetic far field;
- Both warp and weft inserted conductive yarns contribute to EMSE;
- The impedance method (Schelkunoff) [7], which performs an analogy of the discontinuity of shield impedance with a lossy section within a long bifilar

transmission lines, represents the basic source of all adapted relations for EMSE modeling;

- The validation of EMSE analytic relations may be done by measurements of EMSE via Transverse Electromagnetic (TEM) cell system.

2.4.1 Impedance method with correction factors for meshed materials

For flexible, meshed materials like woven fabrics with inserted conductive yarns, the shielding effectiveness in given by Eq. (7) [17]:

$$EMSE = A_a + R_a + B_a + K_1 + K_2 + K_3 \tag{7}$$

Where:
A_a = attenuation introduced by a particular discontinuity, dB.
R_a = aperture single reflection loss, dB.
B_a = multiple reflection correction term, dB.
K_1 = correction term to account for the number of like discontinuities, dB.
K_2 = low-frequency correction term to account for skin depth, dB.
K_3 = correction term to account for coupling between adjacent holes, dB.

Term A_a. A premise for this relation is that the frequency of the incident wave is below the cut-off frequency, given by: $f_c = c/\lambda_c$, with the cut-off wavelength 2.0 times of the maximum rectangular opening. With $a = 5$ **mm** and $\lambda_c = 2\,a = 10$ **mm**, it results a cut-off frequency of $f_c = 30$ **GHz**. Our frequency domain limit being 1 GHz, this premise is fulfilled.

$$A_a = 27.3\left(\frac{h}{a}\right)[\mathbf{dB}] \tag{8}$$

Where:
h = depth of opening (fabric thickness) [cm].
a = width of the rectangular opening perpendicular to E-field (distance between conductive yarns) [cm].

Term R_a. The aperture single reflection loss term depends upon both the impedance of the incident wave and the shape of the aperture.

$$R_a = 20\log_{10}\left(\frac{1+4K^2}{4K}\right)[\mathbf{dB}] \tag{9}$$

Where

$$K = j6.69 \cdot 10^{-5} f \cdot a \tag{10}$$

for rectangular apertures and plane waves,
f = frequency in MHz and.
a, the same significance as above and also expressed in [cm].

Term B_a. The multiple reflection term is given by relation (11):

$$B_a = 20\log_{10}\left(1 - \frac{(K-1)^2}{(K+1)^2}10^{-\frac{A_a}{10}}\right)[\mathbf{dB}] \tag{11}$$

$$\text{valid for}: A_a < 15\ \mathbf{dB} \tag{12}$$

For sample F1 and F2 $a = 5\ \mathbf{mm}$ and with $h_1 = 0.55\ \mathbf{mm}$, respectively $h_2 = 0.49\ \mathbf{mm}$, it result $A_a \approx 3.003\ \mathbf{dB}$ and the premise (12) is fulfilled.

Term K_1. For a source distance from the shield that is large compared with the aperture spacing, the correction term for the number of discontinuities is given by relation (13):

$$K_1 = -10 \log_{10}(S \cdot n)\ [\mathbf{dB}] \tag{13}$$

Where:
S = area of each hole (sq cm).
n = number of holes/sq. cm.

For fabric samples F1 and F2: $S = 0.25\ \mathbf{cm}^2$ and $n = 4/\mathbf{sq\ cm}$, thus $K_1 = 0$ may be neglected. Moreover the term K1 can be ignored for sources close to the shield, which is the case of the TEM cell.

Term K_2. The skin depth correction term is introduced for the reduction of EMSE when the skin depth becomes comparable to the screening wire diameter or the dimension between apertures. An empirical relation was developed for the skin depth correction term (14, 15):

$$K_2 = -20 \log_{10}\left(1 + 35p^{-2.3}\right) \tag{14}$$

Where:

$$p = d/\delta_y \tag{15}$$

As a computation example, the skin depth of silver yarns of fabric sample F2 – with a higher electric conductivity of the yarns than F1, is given by relation (16):

$$\delta_y = \frac{63}{\sqrt{f}}\ [\mathbf{mm}] \tag{16}$$

For frequency $f = 1\ \mathbf{MHz}$ we obtain $\delta_y = 63 \cdot 10^{-3}\mathbf{mm}$.

The term K2 is the single correction factor of the analytic relation sum which encounters the electric parameter of the yarns (electric conductivity and magnetic permeability), within the relation of skin depth. It is thus a factor with high sensitivity on the overall EMSE relation. The electric parameters were considered for the conductive yarn (not for the fabric), since the ratio $p = d/\delta_y$ is a property of the yarn.

Term K_3. Attenuation is relatively high when apertures are tight and the depth of the openings is small compared to the aperture width. This is the result of coupling between adjacent holes and especially important for small openings. The relation is given by (18):

$$K_3 = 20 \log_{10}(\coth A_a/8.686)[\mathbf{dB}] \tag{17}$$

2.4.2 Impedance method with correction between foil and grid

The paper [18] and the handbook [19] propose an analytic relation for EMSE, based on impedance method, with correction between the fabric as a foil and the fabric as a grid. Since at low frequencies, the wavelength λ is much larger than the distance of the aperture opening *a,* the incident radiation sees the fabric as a foil (thin electric materials in relation to the skin depth). At higher frequencies, when the wavelength is comparable with the aperture opening, the grid structure of the fabric becomes relevant (thick electric materials). As such, an exponential function, depending on the frequency f, the dimension of the aperture a and the constant C, was proposed to balance the two relations of EMSE for foil and grid structure - Eq. (18).

$$EMSE = \exp\left(-Ca\sqrt{f}\right)(EMSE)_{foil} + \left[1 - \exp\left(-Ca\sqrt{f}\right)\right](EMSE)_{grid} \tag{18}$$

Where:
a = Distance between conductive yarns [mm].
f = frequency of EM field [MHz].
C = constant.

Analytic relation (18) was firstly introduced for metalized textiles by [18]. The two analytic relations for $(\mathrm{EMSE})_{\mathrm{foil}}$ – the shielding effectiveness of a metallic foil of the same thickness (h) as the fabric and $(\mathrm{EMSE})_{\mathrm{grid}}$ – the shielding effectiveness of an aperture (of size $L\times D$), subjected to a plane wave radiation are given by Eqs. (19, 20) and are valid for metallized textiles:

$$(EMSE)_{foil} = 20\log_{10}\left\{\left[\exp\left(\frac{h}{\delta}\right)\right]\left[\frac{(1+k)^2}{4k}\right]\left[1 - \frac{(k-1)^2}{(k+1)^2}\exp\left(-\frac{2h}{\delta}\right)\right]\right\} \tag{19}$$

$$(EMSE)_{grid} = 100 - 20\log_{10}(a\cdot f) + 20\log_{10}[1 + \ln(a/s)] + 30D/a \tag{20}$$

where:
$k = Z_0/Z_m$ (ratio of wave impedance to shield impedance).
h – thickness of the fabric [m].
δ – skin depth of the material [m].
a – maximum distance between conductive yarns [mm].
s – minimum distance between conductive yarns [mm].
D – depth of the aperture [mm].
f - frequency [MHz].
C = 0.129 (constant).

The constant C is derived by equaling the two relations $(\mathrm{EMSE})_{\mathrm{foil}} = (\mathrm{EMSE})_{\mathrm{grid}}$ and considering the frequency of three skin depths 3δ, as the point below current is negligible in a foil, (95% of the current flows within 3δ) [18].

The Eqs. (18–20) were derived by contribution of [20] in order to be applied for fabrics with inserted conductive yarns. Following conditions apply for the proposed Eqs. (19–20) to be valid for fabrics with inserted conductive yarns:

a. $\sigma \gg \omega\varepsilon$

This condition applies to conductive materials for which $\omega\varepsilon$ is negligible as compared to σ (in metals the condition is practically always fulfilled). This leads to a simplification of *EMSE* relations through the simplification of the shield material impedance definition:

$$Z_m = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}} \approx \sqrt{\frac{j\omega\mu}{\sigma}} \tag{21}$$

Sample F1 has an electrical conductivity σ_{f1} = 41.5 S/m and the electrical conductivity of sample F2 is σ_{f2} = 589 S/m. Since it is considered that the fabrics have the electric permittivity of vacuum ($\varepsilon_0 = 1/36\pi^*10^9$ F/m), the term $\omega\varepsilon$ has a value of 0.055 at a frequency of 1 GHz. Therefore, this condition is fulfilled for both samples in the analyzed frequency range (100 kHz–1 GHz), since the difference between the two terms is of three orders of magnitude for sample F1 (41.5 > > 0.055) and four orders of magnitude for sample F2 (589 > > 0.055).

$b.\ \boldsymbol{Z_m \ll Z_0}$

This condition corresponds to a situation when there is a substantial mismatch between the wave impedance and shield impedance. When this condition is fulfilled, *EMSE* relations greatly simplify as the ratio between the wave impedance and the shield impedance becomes much greater than 1 ($k > > 1$). Thus, Eq. (19) becomes:

$$(EMSE)_{foil} = 20\log_{10}\left\{\left[\exp\left(\frac{h}{\delta}\right)\right]\left[\frac{k}{4}\right]\left[1 - \exp\left(-\frac{2h}{\delta}\right)\right]\right\} \tag{22}$$

By using the simplified version of Z_m, the following values are obtained for the impedance of the two textile samples: 0.21 Ω for F1 and 0.037 Ω for F2 at a frequency of 100 kHz, and 21 Ω for F1 and 3.66 Ω for F2 at 1 GHz. The lowest impedance ratio is $k \approx 18$ for sample F1 at 1 GHz which is still much greater than 1. $k = 103$ for sample F2 at 1 GHz. Therefore, we can say that this condition is fulfilled for both samples in the analyzed frequency range (100 kHz–1 GHz). Note that sample F1, which has lower electric conductivity, fulfills this condition by two degrees of order only for the frequency domain 100 kHz-74.5 MHz. For higher frequencies, the EMSE relation is still valid for F1 but with a greater error, according to [20].

c. $h < 3\delta$ (Thin materials)

It refers to the fact that the thinner the material the higher the reflections from the second interface of the material and thus the re-reflection term in *EMSE* relations is more significant. The amplitude of the incident wave will decrease with about 95% at a distance of three skin depths (3δ) from the first interface inside the material. From the skin depth definition, $\boldsymbol{\delta = 1/\sqrt{\pi f \mu \sigma}}$, one can see that it is lower for materials with higher conductivity and at higher frequencies. For sample F2 (which has a higher conductivity than F1), $\delta \approx 0.66$ mm at 1 GHz and $3\delta \approx 1.98$ mm, which is lower than the fabric thickness ($h = 0.55$ mm) showing that the condition is fulfilled.

These conditions are needed to express relations (19-20) in case of fabrics with inserted conductive yarns according to [20] and are valid both for F1 and F2.

$$\begin{aligned}(EMSE)_{foil} = {} & 168.14 + 20\log_{10}\left(\sqrt{\frac{\sigma_r}{f\mu_r}}\right) + 8.6859\frac{h}{\delta} \\ & + 20\log_{10}\left|1 - e^{-2h/\delta}e^{-j2\beta t}\left(\frac{Z_0 - Z_m}{Z_0 + Z_m}\right)^2\right|\end{aligned} \tag{23}$$

where β is the phase constant.

$$(EMSE)_{grid} = 158.55 - 20\log_{10}(a \cdot f) - 20\log_{10}\sqrt{n} \tag{24}$$

$\boldsymbol{\sigma_r}$ was considered in Eq. (23) the relative electric conductivity of the fabric in relation to the electric conductivity of copper $\boldsymbol{\sigma_{Cu}} = 5.8\ \ 10^7\mathbf{S/m}$. The Eq. (24) is valid for electrically thin materials and square apertures.

C is a constant for woven fabrics with conductive yarns computed in [20], in relation to the electric conductivity of the fabric and the number of apertures of the maximum length of the washer-shaped sample for the TEM cell **Table 3**:

$$C = 1.972 \cdot 10^{-5}\sqrt{\sigma_f\, n} \tag{25}$$

And

$$n = \frac{l_c}{a} \tag{26}$$

With:
n – number of apertures.
l_c – maximum length of fabric for washer-sized sample within TEM cell.
a – distance between conductive yarns.

n	σ_f	C
18	589	0.0005
18	41.54	0.002

Table 3.
Number of apertures and electric conductivity of fabric to compute constant C *according to [20].*

The parameter l_c is needed according to [9] in order to compute the number of apertures of the maximum linear distance. The number of apertures on maximum linear distance are only relevant for EMSE of multiple apertures [9]. *C* is a factor with high sensitivity.

However, relation (24) is valid under certain conditions [20]:

- the maximum number of apertures counts on a linear dimension
- distance between conductive yarns $a < \lambda/2$
- distance between conductive yarns $a >$ thickness h
- the material is thin ($h < 3\delta$) and the n apertures are equally sized

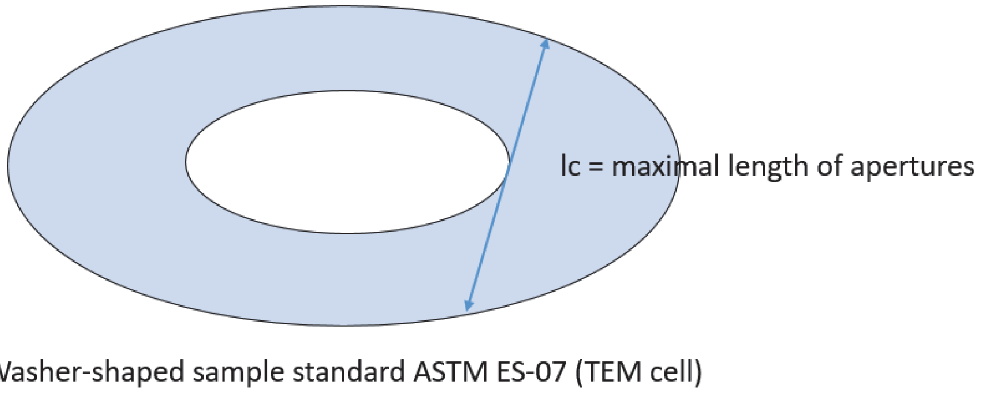


Figure 8.
The maximal distance of the sample for TEM cell meant to compute the number of apertures.

Figure 8 presents the scheme of a washer-shaped sample of TEM cell, with the longest distance, for counting the maximal number of apertures.

The measurements show the values: lc = 75 mm and n = 18 for F1 and F2. These values were used to compute constant C of Eq. (25), in order to be used in general equation of EMSE (18), with Eq. (23) for $(EMSE)_{foil}$ and Eq. (24) for $(EMSE)_{grid}$.

3. Validation of the two analytic relations by the two samples

Both the analytic relation of impedance method with correction factors (described at 2.4.1), and the analytic relation with correction between foil and grid (described at 2.4.2), were applied for sample F1 and sample F2, by introducing the electric and geometric parameters of the samples and generating the related EMSE diagrams.

Figures 9 and **10** present the modeled and the measured values in case of the relation of impedance method with correction factors for F1 and F2.

Figures 9 and **10** show a good modeling of the impedance method with correction factors, both for the fabric with stainless steel yarns and the fabric with silver yarns. The analytic relation (7) shows for the fabric with stainless steel yarns a maximal difference to the measured values of about 10 dB at the frequency of 10 MHz and has for the frequency domain of 0.1–1 MHz and 100–1000 MHz, close values with maximal differences of 2–5 dB. Same analytic relation shows for the fabric with silver yarns a maximal difference to the measured values of 5 dB, especially in the end points of the frequency domain, namely 0.1 MHz and 1 GHz. **Figures 11** and **12** present the modeled and the measured values in case of the relation with correction between foil and grid for F1 and F2.

Figures 11 and **12** show a good estimation of EMSE by relation with correction factor between foil and grid, both for the fabric with stainless steel yarns and the fabric with silver yarns. The analytic relation (18) shows a mean difference to the

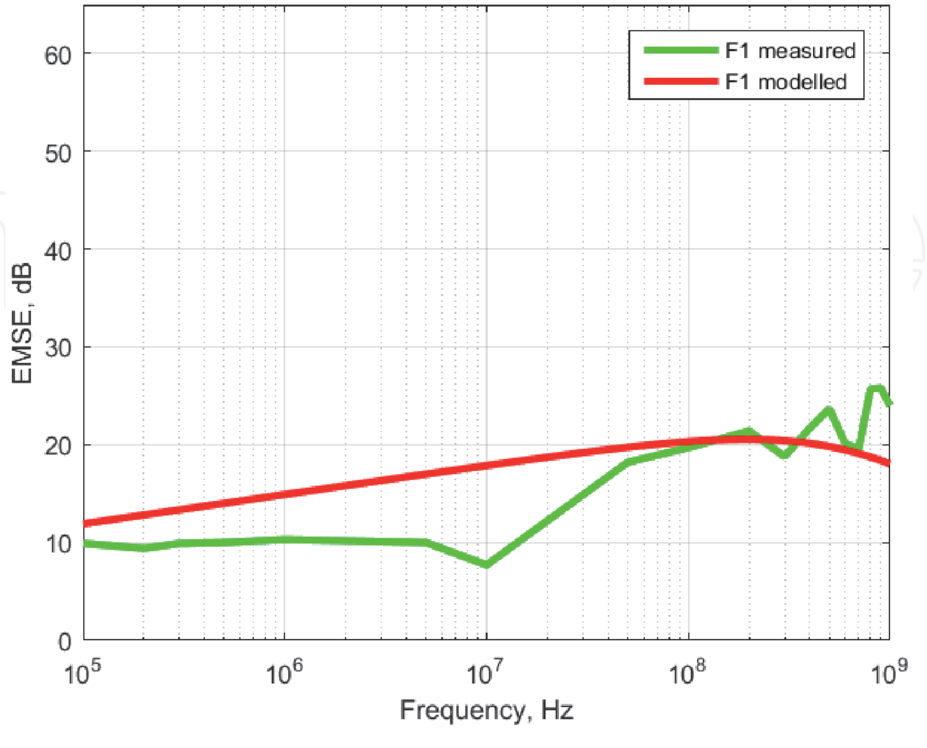


Figure 9.
F1 (stainless steel) – Modeled (7) and measured.

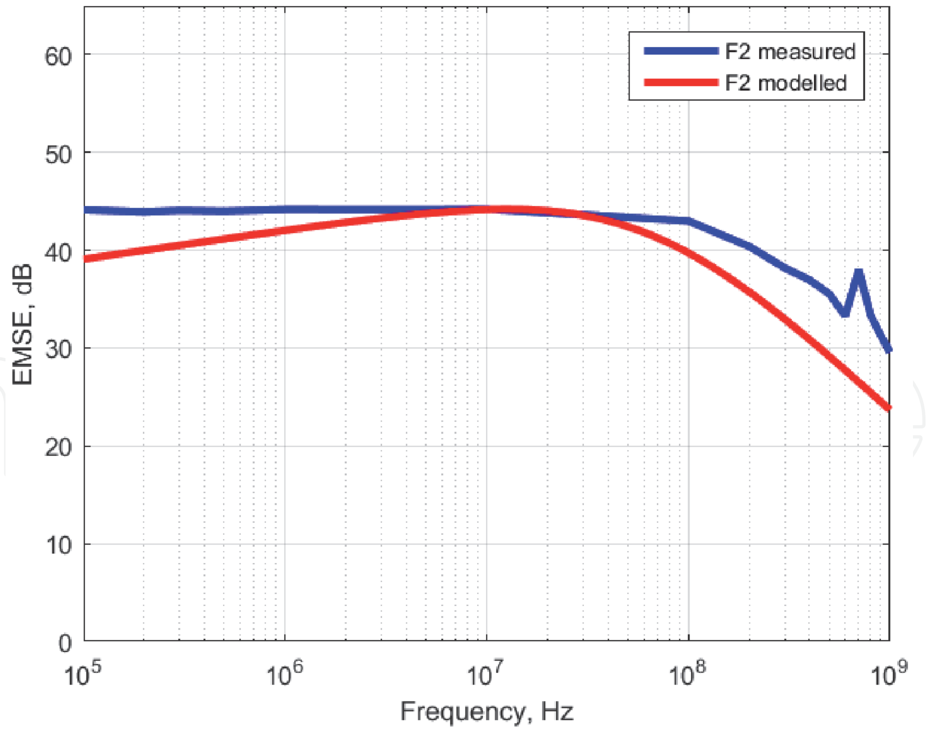


Figure 10.
F2 (silver) – Modeled (7) and measured.

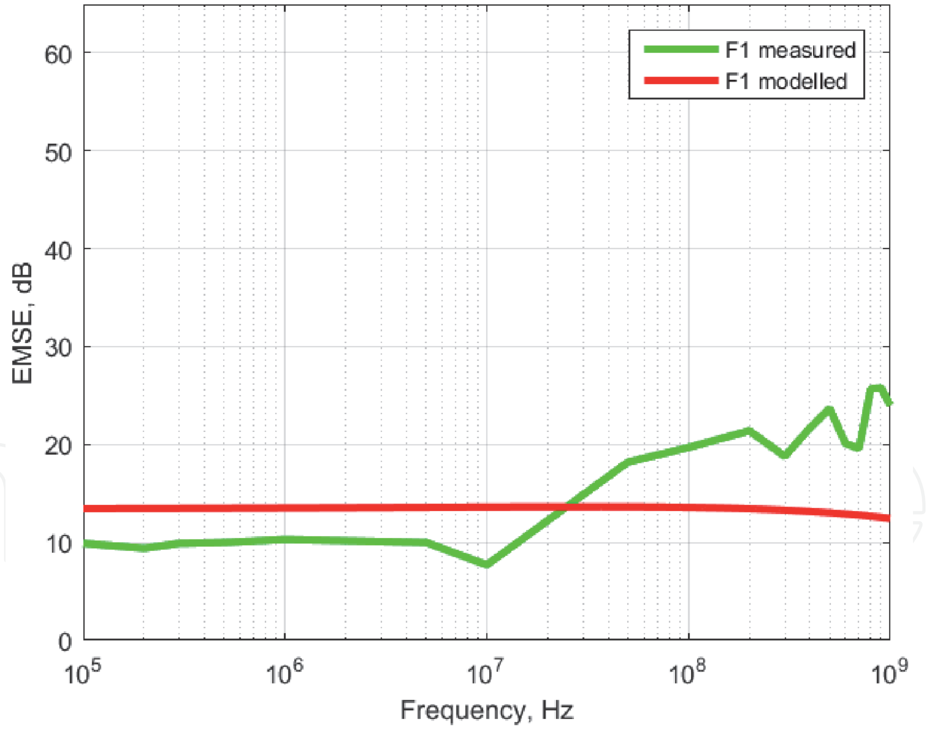


Figure 11.
F1 (stainless steel yarns) – modelled (18) and measured.

measured values of 5–10 dB on the frequency domain for F1 and a mean difference to the measured value of 9–10 dB on the frequency domain for F2.

The two methods for estimating EMSE in case of fabrics with inserted conductive yarns, relay on different principles of analytic relations. Both methods use as input parameters the electric and geometric parameters of the fabric. These electric

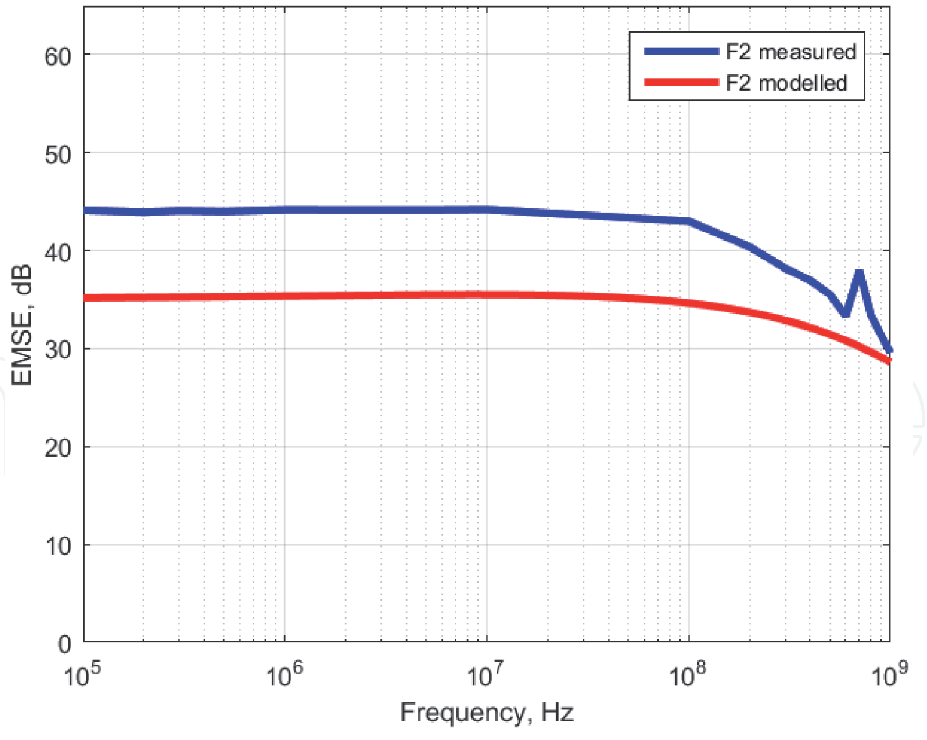


Figure 12.
F2 (silver) – modelled (18) and measured.

and geometric parameters were presented with same notations for the two methods, since the scientific literature tackles the methods individually and presents the parameters with various notations [17–20].

Two types of fabrics with inserted conductive yarns, having similar structure, but different raw materials for the conductive yarns, namely stainless steel and silver, were used to validate EMSE by the two methods, based on experimental data.

Some of the parameters of the two methods have greater significance in overall estimation of EMSE, some have less significance. This aspect is tackled by the sensitivity analysis.

As such, for the first method, all factors of relation (7) do not depend on frequency, neither on the electric parameters of the fabrics, except of the factor *K2*, which is expressed as ratio between yarn diameter $\boldsymbol{d}$ and yarn skin depth $\boldsymbol{\delta_y}$. *K2* is the single factor depicting the electric parameters, since the relation of skin depth for the conductive yarn of the fabric includes frequency, magnetic permeability and electric conductivity. By analyzing influence of each factor for general outcome of EMSE, it results that factor *K2* has the most significant influence and this is due its characterization of the electric parameters of the fabrics.

The second method aims to balance the relations of EMSE for the foil and for the grid, depending on frequency and the related thin or thick electric material. Main parameter with significant influence in this regard is the constant *C*. This constant depicts the balance between the EMSE of the foil and EMSE of the grid. Constant *C* was computed according to [20] depending on electric conductivity of the fabric and number of apertures on the longest distance of the washer-shaped fabric sample for the TEM cell (according to standard ASTM ES-07).

The geometric parameters of fabrics have for both methods an important significance too, however with less sensitivity than the electric parameters.

Another aspect to be tackled is the tolerance of the EMSE measurement via TEM cell system according to standard ASTM ES-07. The contour of the washer-shaped samples was coated with silver paste in order to ensure a good electric connection to the metallic parts of the TEM cell. Since EMSE was measured as ratio between the electric power values without and with material present and all measurement devices have they own tolerance (network analyzer, amplifier, TEM cell connection), the overall measurement error could be estimated at 3–4 dB.

As such, EMSE values were compared between models of estimation based on electric a geometric parameters of the fabric and experimental measurements. It can be stated that the validation approach has an indicative character. By comparing validation results of the two analytic relations (7) and (18) we may conclude that analytic relation (7) has closer values to experimental data. However, both relations have close values to the experimental values of EMSE and may be used to predict this special functionality of fabrics. Design of fabrics for electromagnetic shielding applications may be supported by both methods.

4. Specified requirements of electromagnetic shielding textiles

The designer of fabrics may relate on the document [FTTS-FA-003 v2], in order to evaluate what the needed requirements are for fabrics destined for EM shielding. This document states the limits of EMSE for fabrics of professional and general use (**Tables 4** and **5**).

According to the specification, F2 (silver yarns) has for professional use a good EMSE in the frequency domain of 0.1–100 MHz and a moderate EMSE in the frequency domain of 100–1000 MHz. Moreover, the same fabric sample F2 has for general use an excellent EMSE in the frequency domain of 0.1–100 MHz and a very good EMSE in the frequency domain of 100–1000 MHz.

The sample F1 (stainless steel yarns) has professional use a fair EMSE in the frequency domain of 100–1000 MHz, while for general use the same sample has a very good EMSE. For general use in the frequency domain of 0.1–100 MHz, sample F1 has good EMSE.

These considerations prove that the achieved fabric sample may be successfully used as electromagnetic shields for various applications, with different grades of EMSE on the frequency domain.

Grade	**5** **Excellent**	**4** **Very good**	**3** **Good**	**2** **Moderate**	**1** **Fair**
EMSE range	EMSE>60 dB	60 dB ≥ EMSE >50 dB	50 dB ≥ EMSE >40 dB	40 dB ≥ EMSE >30 dB	30 dB ≥ EMSE >20 dB

Table 4.
Class I – Textiles for professional use.

Grade	**5** **Excellent**	**4** **Very good**	**3** **Good**	**2** **Moderate**	**1** **Fair**
EMSE range	EMSE>30 dB	30 dB ≥ EMSE >20 dB	20 dB ≥ EMSE >10 dB	10 dB ≥ EMSE >7 dB	10 dB ≥ EMSE >7 dB

Table 5.
Class II – Textiles for general use.

5. Discussion on structure–property relationship of EM shielding fabrics

The two proposed models have high relevance in product development for EM shielding applications. By having set the target EMSE value and the frequency of the application (**Tables 4** and **5**), one of the first choices is selection of the raw material for the conductive yarn (stainless steel, silver, copper etc.). The quantity (mass) of conductive yarn leads to a cost-effectiveness calculation for the shielding fabric. A second fabric parameter to be designed is the distance between conductive yarns a. A tighter distance between conductive yarns a, means a higher EMSE, according to both methods (7) and (18). On the other hand, too tight conductive yarns are critical, due to technological limitations on non-conventional weaving machines destined for insertion of conductive yarns with metallic content.

Other fabric parameters, such as weave, density and yarn count are third choice to design EM shields. Although, none of the presented models depicts these parameters, some other important properties of fabrics, such as mechanical resistance, flexibility and drape highly depend on these parameters.

Basically, the proposed models offer a quick overview of the functionality of shielding, especially useful when starting designing a fabric.

6. Conclusion

This book chapter tackles electromagnetic shielding as an important functionality to be achieved by textile materials. In order to be estimate this functionality, quantified by the electromagnetic shielding effectiveness (EMSE), the book chapter proposes two analytic models from the scientific literature [7, 20]. The approach of modeling EMSE offers to the textile designer relevant insight on the relation between fabric properties and shielding functionality. Most relevant electric and geometric parameters of woven fabric shields were considered within the analytic models, such as: fabric thickness, conductive yarn's diameter, distance between conductive yarns, electric conductivity and magnetic permeability of yarns and fabrics.

The two analytic relations were meant to be validated by experimentally measured woven fabrics with inserted conductive yarns out of stainless steel and silver. EMSE was measured for both these fabrics via TEM cell system, according to the standard ASTM ES-07. The experimental results show that both analytic relations have a good estimation of EMSE with a maximum difference on the frequency domain 0.1–1000 MHz of 5–8 dB. Moreover, the achieved fabrics show effective EMSE values according to the requirements specifications of textile shields for general and professional use.

In conclusion, the proposed analytic models do support the textile engineer in designing woven fabrics, to achieve desired shielding functionality. Some technological aspects regarding textile processing should be also considered, like limitations of inserting the metallic yarns on non-conventional weaving machines, achieving desired mechanical resistance properties by modifying yarns density of fabrics and overall cost-effectiveness of using expensive yarns with metallic content. This contribution was possible by interdisciplinary knowledge of textile field and electromagnetic compatibility field.

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