Chapter

Life Cycle Assessment of Flexible Electromagnetic Shields

Ion Răzvan Rădulescu, Lilioara Surdu, Emilia Visileanu, Bogdana Mitu and Cristian Morari

Abstract

Nowadays, fiber based flexible electromagnetic shields have widespread applications in ensuring Electromagnetic Compatibility (EMC). Shielding is a solution of EMC, and the main methods to estimate shielding effectiveness are represented by the circuit method and the impedance method. Magnetron sputtering of metallic layers represents a novel technique to impart electric conductive properties to fabrics. Coating of fabrics represents a second main option to manufacture textile shields beside the insertion of conductive yarns in the fabric structure. Life Cycle Assessment (LCA) is often used to assess a comparatively modern with a classical manufacturing process in order to prove its eco-friendly character. This chapter comparatively assesses flexible EM shields manufactured of fabrics with inserted conductive yarns with and without magnetron plasma coating. The copper plasma coating of cotton fabrics with inserted silver yarns increases shielding effectiveness (EMSE) by 8–10 dB. In order to keep for the LCA study the same functional unit of 50 dB at 100 MHz for one sqm of fabric, the fabric structure is modeled with a reduced distance between the inserted conductive yarns. Results of the LCA study show a substantial impact on the environment for the plasma coated fabric upon using a laboratory scale deposition set-up.

Keywords: LCA, EMC, textiles, magnetron plasma, copper coating, silver yarns, woven fabrics

1. Introduction

This book chapter tackles a highly interdisciplinary theme: a Life Cycle Assessment (LCA) study of plasma coated textiles for electromagnetic interference (EMI) shielding. Thus, the introduction presents some indicative aspects for all these particular domains.

1.1 EMI shielding textiles

The textile materials destined for Electromagnetic Interference (EMI) shielding include some additional properties when compared to metallic shields, according to the latest research studies [1–5]:

- A significant electromagnetic shielding effectiveness (EMSE - expressed in dB), as the main functionality of the textile shield, with values in the range of 30–80 dB;

- Lightweight, flexibility, adaptability to the shape and mechanical resistance;

- Preservation of specific textile properties like drape, bending and resistance to repeated washing;

- Sustainable and eco-friendly character by the application of the new technologies;

- Cost-effectiveness based on these new manufacturing technologies.

The additional functionalities offer added value to the textile substrates. Starting from the research phase, the textile shields may be used as promising EM shields in numerous applications, such as civil and military EMI protection, medical devices, or the buildings' EMI shielding. All these applications tackle the attenuation of EMI, needed for the proper functioning of electronic equipment (by electromagnetic compatibility principles), and the protection of living beings against non-ionizing radiation (medicine).

As known from the literature, there is a strong correlation between the electrical conductivity of the textile shield [S/m] and their electromagnetic shielding effectiveness [dB] [6]. Eddy currents induced by the incident EM field generate an opposed EM field, with an attenuating result [7]. Some of the recent advances in manufacturing textile shields with additional properties include integrating various electric conductive raw materials into the fabric structure [1–5].

An eco-efficient method to manufacture a hydrophobic textile substrate with excellent EM shielding properties by carbon nanotubes and graphene dispersion is presented in [1]. Various solutions of manufacturing textile shields by preserving the specific properties of textiles, such as good air permeability, good bending, flexibility, and stability in a hot and wet environment, were achieved by polymerization of Pyrrole and subsequent coating with Nickel [2]. Additional resistance to washing and end-applications of the electric conductive fabric as patch antenna are included in [2]. Carbon nanotubes with nanometer deposition of copper layers were integrated into fabrics for EM shielding [3]. Additional mechanical resistance properties were proved on the achieved fabrics [3]. The special properties of intrinsic conductive polymers (Pyrrole) are presented within the review paper [4]. Another contribution to EM shields was achieved by sintering silver on the fabrics, however, with a significant decrease of EMSE after repeated washing cycles [5]. Hence, textile EM shields combine the EMI shielding properties with the specific advantages of textile fabrics.

1.2 Methods to estimate shielding effectiveness

The main methods to estimate shielding effectiveness based on material properties are represented by the impedance and circuit methods [6]. Several physical premises apply for each of the methods. Both methods consider an infinite perpendicular plane shield to the incident EM field. While the impedance method is valid for the electromagnetic far field, the circuit method is valid for the near field.

For woven fabrics with inserted metallic yarns in warp and weft direction, the resulting conductive grid structure may be modeled by the impedance method with correction factors [8]. Adaptation of this method for textiles may be found in [9].

Another method for modeling conductive grid structures by balancing EMSE of the grid with EMSE of the sheet, with regard to the electric thin materials, was provided by [10, 11], with specific adjustment for textiles [9, 12]. Further contributions to model EMSE of woven fabrics with metallic yarns were provided by analogy with an RLC circuit [13] and by analogy with small aperture antennas [14].

The main material constants used for modeling EMSE of textiles are electric conductivity and magnetic permeability of the metallic yarns and the composite fabrics, the optical diameter of the yarn/fabric thickness, distance between metallic yarns in the fabric structure. The skin depth of yarns/fabrics has a great significance both in the circuit method and in the impedance method with correction factors [9, 15].

1.3 Magnetron plasma sputtering of textiles

Textile shields are usually manufactured by two main methods: inserting metallic yarns into the fabric structure and coating with metallic layers [16]. While the insertion of metallic yarns by weaving, knitting, and nonwoven making already represents the classical method, the coating of nanometer scale metallic layers by magnetron plasma represents a modern, promising technique. The main advantage of the plasma coating is the enhancement of EMSE and preservation of flexibility of the fabrics by the nanometer thickness [17].

The copper coating onto the textile fabrics was performed at INFLPR into a dedicated stainless steel spherical vacuum chamber (K.J. Lesker, UK), pumped out by an assembly of afore pump and turbomolecular pump (Pfeiffer, DE), which allowed obtaining of a base pressure down to 3×10^{-5} mbar. A constant argon flow (purity 6.0) of 50 sccm was continuously introduced into the chamber by means of a Bronkhorst mass flow controller, which allowed to establish the processing pressure around 5×10^{-3} mbar. The chamber is provisioned with a rectangular magnetron sputtering gun from K.J. Lesker, accommodating the high purity copper target. The discharge was ignited by a radio frequency generator (13.56 MHz) provisioned with an automatic matching box for adapting the impedance and the deposition time was set to ensure coating thicknesses of 1200 nm on each side of the textile fabric. Enhanced deposition uniformity was achieved by rotating the samples during the deposition process (200 rotations/ min). **Figure 1** presents a sketch of the experimental set-up of the magnetron plasma equipment of INFLPR.

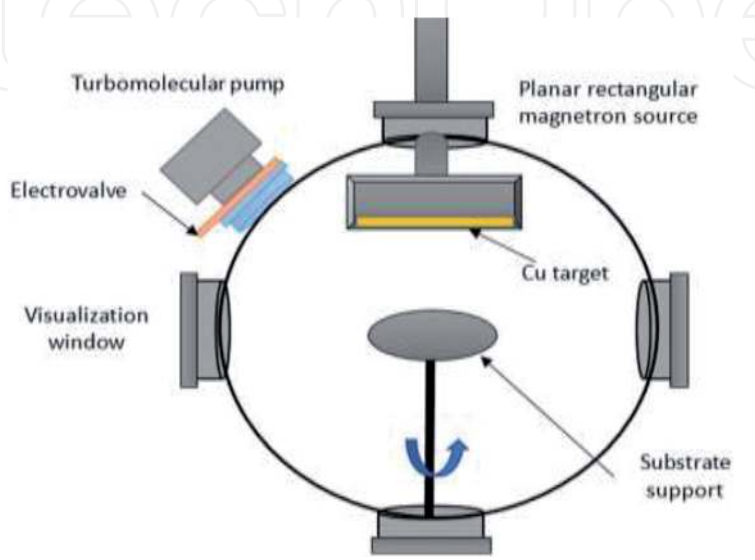

Figure 1.
Sketch of the experimental set-up in INFLPR utilized for copper coating of textiles.

1.4 Life cycle assessment of textiles

Life Cycle Assessment (LCA) studies are conducted according to the standard ISO 14040 [18]. The standard specifies four phases of an LCA study: i) the Goal and scope, ii) the Life Cycle Inventory (LCI), iii) the Life Cycle Impact Assessment (LCIA), and iv) the Interpretation (including the Sensitivity Analysis). **Figure 2** presents graphically this approach, as well as some of the main applications:

The Goal and scope phase defines the aim of the study as well as its limitations. LCA studies may be conducted for various reasons, such as benchmarking for different products, identifying Key Environment Performance Indicators (KEPI), motivating green acquisitions, or comparative assessment between a modern and a classical technology [19]. The latter application is used mainly for research to prove the environmentally friendly character of modern technology [20].

The Life Cycle Inventory (LCI) phase means collecting for the product or process the inputs and outputs into the system, such as electric energy, heat, raw materials, auxiliary substances, transport, etc. The Life Cycle Impact Assessment (LCIA) phase is usually supported by software applications. The inputs and outputs into the system are discretized in elemental units upon the environment, included within a data basis, and computed by the software application on impact categories. Impact categories characterize various aspects of the impact on the environment and are grouped in specific methods. The EcoIndicator 99E method includes impact categories such as carcinogens, ozone layer, fossil fuels, ecotoxicity, etc. It is based on the calculation of the damages to Human Health, Ecosystem Quality, and Resources [21]. More examples of methods include ReCiPe (which includes global warming, terrestrial acidification, water consumption, etc.) [22] and IMPACT2002+ refereeing human health, ecosystem quality, climate change, and resources in a combined midpoint/damage structure [23].

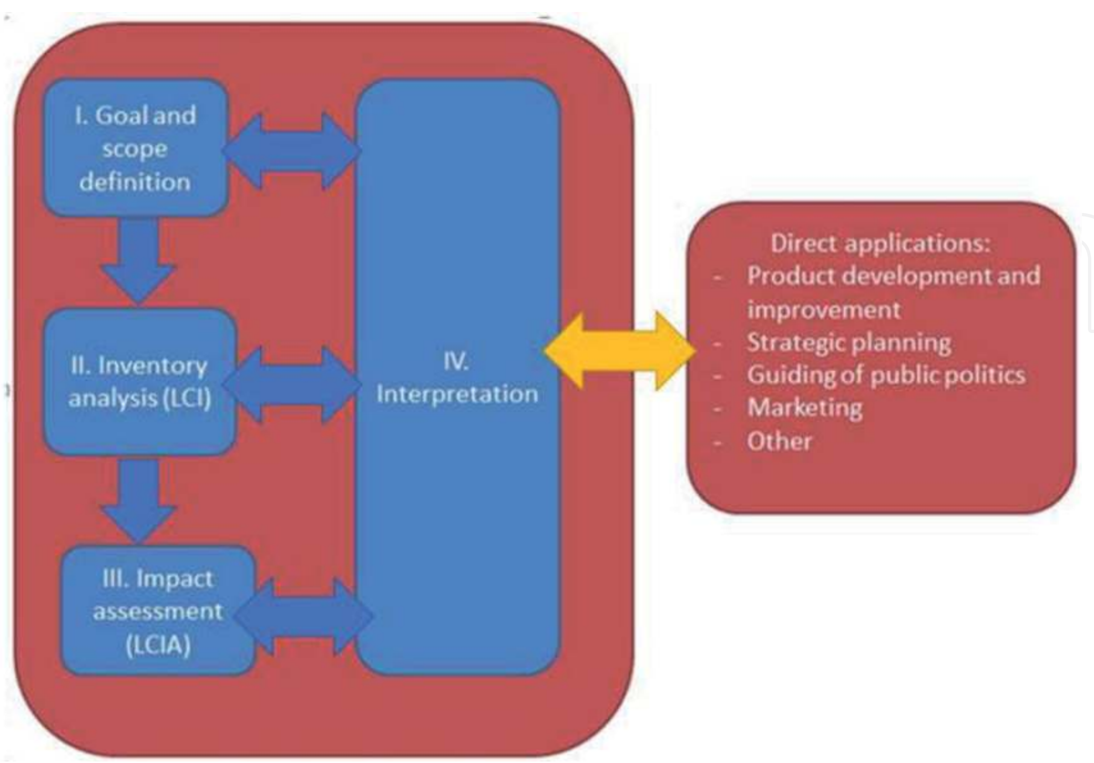

Figure 2.
The four phases of LCA accordingly to the Standard 14040 [18].

The SimaPro7 software and the EcoInvent 3.0 data basis were used in our study [24, 25]. The following types of LCIA diagrams may be generated by the software, according to the following principles:

- Characterization: Impact on the environment is computed by characterization factor of each specific substance;
- Normalization: Impact categories are related to a common reference;
- Weighting: Impact categories are weighted according to their specific relevance;
- Single score: Presents the impact categories on a single column and is useful for comparative assessment.

The functional unit in a comparative LCA study represents the common reference for the two products or processes [19]. Some of the recent advances in LCA for textile materials include the following literature studies [26–30]. LCA studies were used to foster decisions for implementing new technologies on the management level of SMEs [26]. The research was accomplished on LCA studies for textile raw materials, namely cotton, polyester, nylon, acryl, and elastane, within a benchmarking study [27]. The research was directed towards LCA for various treatment processes on textiles, such as the fireproof treatment of fabrics and its environmental impact reduction by eco-path disposal treatment [28]. Three different recycling PES trousers (chemical/ mechanical and energy recovery) were analyzed in [29].

Moreover, attention was focused on LCA for smart and e-textiles with conductive fibers made of conjugated polymers, carbon nanotubes, graphene, polymer blend, or nanocomposite [30]. Eco-design in smart textiles plays an important role: a comparative LCA study for eco-designed and original smart textiles products was achieved in [31]. End-of-life and recycling management of the textile chain was analyzed by LCA in countries such as Finland [32] and Denmark [33]. A review of the overall impact of nanomaterials on the environment was performed in [34].

1.5 Aim of this book chapter

The aim of this chapter is to comparatively assess the impact on the environment of two types of electromagnetic shields:

- Woven fabric with inserted silver yarns in warp and weft (**Figure 3**);
- Woven fabric with inserted silver yarns in warp and weft and magnetron plasma copper coating (**Figure 4**).

EMSE was experimentally determined according to the ASTM ES-07 (TEM cell) standard and represented in **Figure 5**.

Since magnetron sputtering copper coating enhances the shielding effectiveness of the woven fabrics with 8–10 dB on the frequency domain of 0.1–1000 MHz, the woven fabric with inserted metallic yarns was modeled considering a smaller distance of the grid in order to reach the same EMSE. The increase of EMSE in smaller grid distances is given by relations of the EMC literature [6]. This approach was considered in order to have the same LCA functional unit for both textile shields, namely: **one sqm of shielding fabric with 50 dB at 100 MHz.**

Figure 3.
Woven fabric with inserted silver yarns in warp and weft.

Figure 4.
Same woven fabric with plasma copper coating.

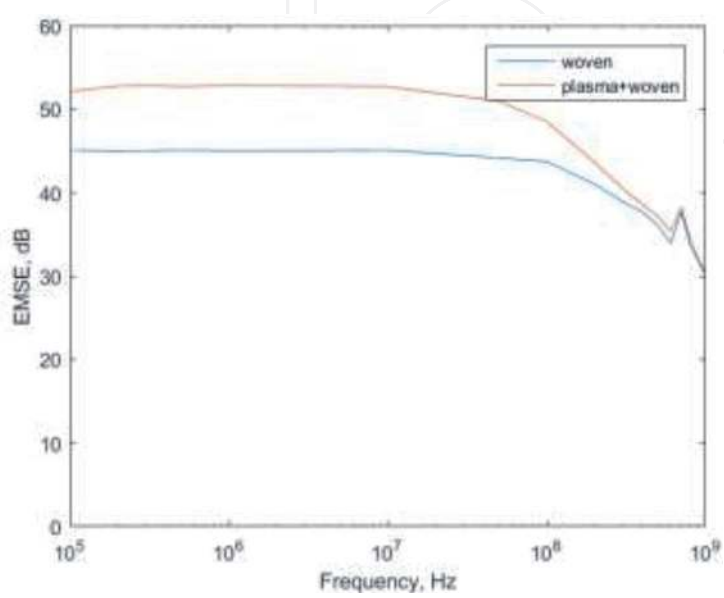

Figure 5.
Experimental EMSE values for the woven fabric with conductive yarns (blue) and the plasma coated woven fabric with conductive yarns (red).

Yarn code	M1	M2
Yarn type	100% Cotton, spun yarn	Silver coated PA yarn (Shieldtex 117/17 dtex)
Linear density [Nm, dtex]	Nm 50/2	140x2 dtex
Linear electrical resistance [Ω/m]	—	220
Linear electrical conductivity [S/m]	—	121842
Relative Magnetic Permeability [1]	1	1
Optical diameter [μm]	293	218

Table 1.
The yarn's properties.

2. Comparative LCA on plasma coated woven fabrics with conductive yarns destined to EMI shielding

2.1 The design of the textile shields

The woven fabric with inserted metallic yarns was manufactured at SC Majutex SRL, a woven fabric producer of technical textiles (www.majutex.ro). **Table 1** presents the physical-mechanical and electric properties of the cotton and silver yarns used for the fabric weaving, while **Table 2** presents the physical-mechanical and electric properties of the resulted fabric.

The woven fabric was manufactured by an industrial weaving process on SOMET weaving machines with a width of 1.90 m.

2.2 The modeling of the woven fabric with conductive yarns

The following relations of electric conductive grids from the EMC literature was applied to model the woven fabric with silver yarns by reducing the distance of the grid in order to increase EMSE [14]:

$$EMSE = 20\log\left(\frac{\lambda / 2}{W\sqrt{\pi}}\right) \quad (1)$$

Yarn type	Woven fabric system	M1 + M2
Float repeat (cotton yarns: silver yarns) SR6431:2012	Warp	6:2
	Weft	5:2
Fabric Density [no.yarns/10 cm] EN1049–2:2000	Warp	168
	Weft	150
Distance between Conductive Yarns *W* [mm]	Warp	5
	Weft	5
Fabric Thickness, [mm] ISO5084:2001	—	0.490
Specific Mass, [g/m^2] EN12127:2003	—	118

Table 2.
The woven fabric properties.

$$W = \frac{\lambda}{2\sqrt{\pi}} \times 10^{-\frac{EMSE}{20}} \quad (2)$$

With W = distance between metallic yarns in a woven fabric structure.λ = wavelength of the incident EM field.

According to the model (**Figure 6**), the distance of the electric conductive grid has to shift from W = 5 mm to W = 3 mm, in order to increase the EMSE of the woven fabric by 8 dB at 100 MHz. Since the functional unit for the comparative LCA study was set to one sqm of shielding fabric with 50 dB at 100 MHz; it resulted in two variants of textile shields:

1. Woven fabric with inserted metallic yarns with the distance of 3 mm

2. Plasma coated woven fabric with inserted metallic yarns with the distance of 5 mm

The next step was to collect the LC Inventory data for these two EM shields.

2.3 The LC inventory data

LCI includes all the inputs and outputs into the system, such as raw materials, electricity consumption, auxiliary materials, etc. **Table 3** presents the mass per sqm for the two textile shields: sample 1 is manufactured, and sample 2 is modeled. Sample 1 was subsequently coated by magnetron plasma.

The LCI of silver yarns was computed by considering the ratio of Silver and PA6.6 mass of the Statex Silver yarn [35] and mean data for the spinning process [27]. The LCI of copper coated fabrics was computed by considering the mass

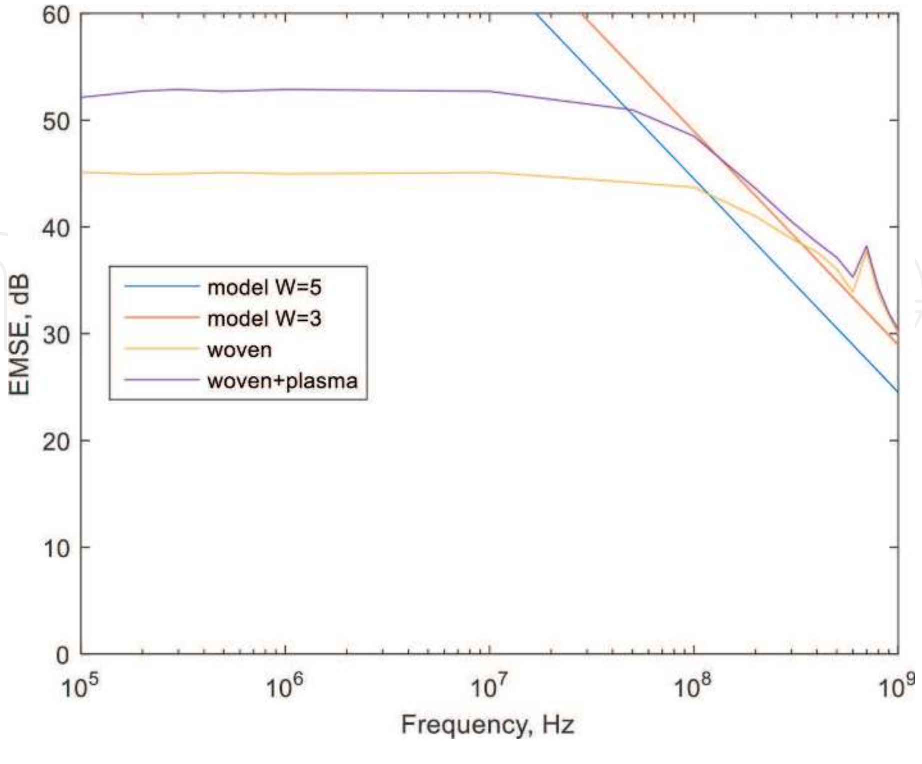

Figure 6.
Modeled and experimental EMSE.

Samples		Cotton yarns [g/sqm]	Silver coated PA yarns [g/sqm]	Silver content out of yarn [g/sqm]
Sample 1 W = 5 mm	Warp	51,84	6,08	3,73
	Weft	46,22	6,51	4,00
	Total	**98,06**	**12,59**	**7,73**
Sample 2 W = 3 mm	Warp	41,47	9,73	5,98
	Weft	38,88	9,13	5,61
	Total	**80,35**	**18,86**	**11,59**

Table 3.
Specific mass for the woven structure with silver yarns.

Input/output into the system	Value	Unit
Functional unit: 1 sqm of shielding fabric with 50 dB at 100 MHz		
Cotton yarn (product)	98.06	g
Silver Statex yarn (product)	12.59	g
Argon, liquid, at the plant	100	g
Copper, primary, at the refinery	50	g
Electricity, low voltage, at grid/RO	0.46	kWh
Weaving Majutex (process)	110	g

Table 4.
LC inventory – Sample 1 (plasma coated woven fabric).

Input/output into the system	Value	Unit
Functional unit: 1 sqm of shielding fabric with 50 dB at 100 MHz		
Cotton yarn (product)	80.35	g
Silver Statex yarn (product)	18.86	g
Weaving Majutex (process)	110	g

Table 5.
LC inventory – Sample 2 (modeled woven fabric).

of copper, the energy consumption of the magnetron sputtering equipment for laboratory scale deposition, and the release of Argon into the air (data provided by INFLPR). LCI data is included within **Tables 4** and **5**.

The main challenge of the comparative LCA study is the additional Silver coated yarn needed for the grid of W = 3 mm related to the plasma copper coating of 1200 nm on both sides of the fabric with the grid of W = 5 mm. The manufacturing process of the PA6.6 coated silver yarns was estimated with mean values according to the spinning processes of various raw materials based yarns [27]. Single main input/output factors into the system were considered within the indicative LCA study. Limitations applied for transport, heat, etc., of the industrial weaving process at SC Majutex SRL. INFLPR provided the magnetron sputtering inputs/outputs into the system.

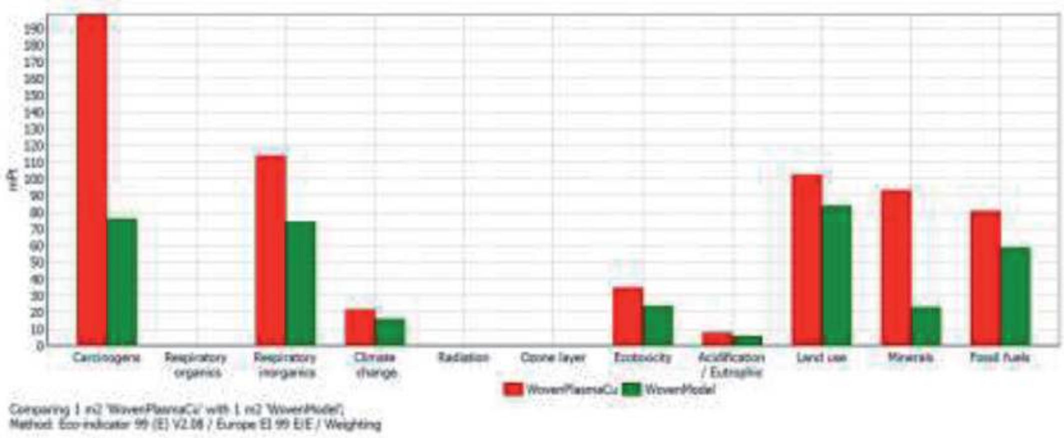

Figure 7.
Comparative weighting diagram: Sample1 (red) and Sample2 (green).

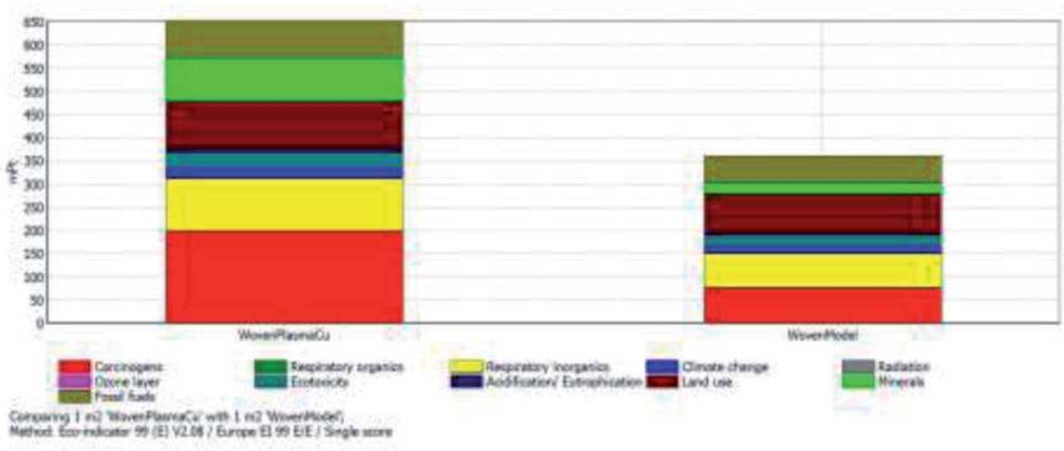

Figure 8.
Comparative single score diagram: Sample1 (left) and Sample2 (right).

2.4 Life Cycle Impact Assessment diagrams

By introducing the LCI data into the SimaPro software, the following LCIA diagrams resulted:

Figure 7 presents the comparative impact of the two textile shields on impact categories of the method EcoIndicator 99E. The main negative impact on the environment is given by the carcinogens followed by Respiratory inorganics, which could be explained by releasing Argon into the air within the plasma process. Another wide difference between the two shields is at the impact category Minerals, while Fossil fuels for electric energy are quite balanced.

The Single score diagram (**Figure 8**) presents the total comparative impact on the environment for the two textile shields by a single view. One of the processes is industry (weaving of metallic yarns – Sample 2), and the other process is of laboratory (coating with metallic layers – Sample 1), which is why manufacturing one sqm of shielding fabric has a significant impact on the environment in the laboratory process. The corresponding LCIA data of the two processes offers significant differences when related to the functional unit.

2.5 Scale-up of plasma equipment

One of the LCA study consequences is the need to scale up the plasma equipment for industrial use. A business plan considering the investment for the

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equipment and the Return-On-Investment and Break-even point analysis has been done and will be published in the near future. The scale-up magnetron plasma equipment represents the key expertise of INFLPR. Textile shields properties are key expertise of INCDTP and the experimental set-up for EMSE measurement expertise of ICPE-CA.

3. Conclusion

This chapter has included theoretical aspects and applications within a highly interdisciplinary domain: electromagnetic compatibility, plasma physics, textiles, and Life Cycle Assessment. Textile EM shields have been manufactured by two methods – insertion of metallic yarns and plasma coating of metallic layers and their shielding effectiveness has been experimentally determined. In order to assess the environmentally friendly character of plasma coating, a comparative LCA study has been conducted between the woven fabric with conductive yarns and the plasma coated woven fabric. One sqm of shielding fabric with 50 dB at 100 MHz has been considered as a functional unit. Since plasma coating enhances EMSE with 8–10 dB on the frequency domain of 0.1–1000 MHz for the woven fabric with metallic yarns, the grid of the woven fabric with metallic yarns has been reduced in order to reach the same EMSE. Modeling according to relations from the EMC literature has been applied for this purpose. The main challenge of the comparative LCA study has been the relation between additional metallic yarns for the model and the plasma coating of the woven fabric. Since the plasma coating is a laboratory process, the impact on the environment was higher. A business plan has been achieved to implement a scale up plasma equipment for industrial use. Further research is needed to evaluate the eco-friendly character of textile electromagnetic shields.

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