Comptes Rendus

Life Cycle Assessment of RFID tags

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Contents

Abstract. *In response to the increasing demand for energy-efficient and eco-friendly communication systems, there has been a surge of interest in communication based on backscatter modulation, which involves passive labels. These systems utilize the radar signature of a label with printed elements specifically designed to perform desired functions, thus eliminating the presence of batteries and microchips, which are very polluting components. Although they may not have the same level of functionality as those with a power supply or chip, they can still be useful for applications that require a reading distance of up to one meter. Backscatter communication provides several advantages over barcodes, including the ability to read through certain opaque objects and faster acquisition time. This research focuses on the environmental impact of three identification tags that represent these technologies namely UHF RFID (integrate microchips and batteries), chipless RFID (backscatter modulation), and barcodes, used in the electronics industry. The objective is to conduct a Life Cycle Assessment of these technologies to understand their carbon footprint and compare their sustainability. The lab work will use tools such as "OpenLCA" to evaluate the environmental impact of these technologies. The findings of this research will provide insights into the sustainability of different identification technologies and help identify ways to reduce the environmental impact of the electronics industry.*

Keywords. Chipless radio frequency (RF) identification (RFID), RFID chip tags, barcodes, Life Cycle Assessment, environmental impacts,

1. Introduction

The electronics industry is one of the major contributors to global carbon emissions, and the impact of human activity on the environment is becoming increasingly evident. To reduce our carbon footprint, we need to understand the impact of the things we produce and consume, and the electronics industry is at the heart of this challenge. In particular, the identification sector is a key area where it is essential to have figures on the carbon footprint of the implemented technologies. This research focuses on three identification technologies used in the electronics industry: UHF RFID, chipless RFID, and barcodes. These technologies have different levels of functionality and environmental impact, and understanding their carbon footprint is crucial to reducing the environmental impact of the electronics industry. The objective of this research is to conduct a Life Cycle Assessment of these technologies to understand their environmental impact and compare their sustainability. The research will use tools such as "OpenLCA" (an open source and free software for Sustainability and Life Cycle Assessment) to evaluate the environmental impact of these technologies. The findings of this research will provide insights into the sustainability of different identification technologies and help identify ways to reduce the environmental impact of the electronics industry.

The development of electronic devices has introduced non-natural interactions that require significant expertise and time investment. Despite significant progress in wireless technologies, the need for a battery restricts their use. Researchers are, therefore, interested in developing electronic systems that communicate wirelessly and without batteries. Radio Frequency Identification (RFID) tags, which consist of an antenna and a self-powered chip, have been used for identification. While many studies have extended the functionality of these tags, they are still based on the use of a silicon chip, which even if they are covered with dust, dirt, or other materials, as long as they are within range of the reader.One of the major advantages of chipless RFID is that it eliminates the need for an electronic chip, which is one of the major cost drivers in traditional RFID tags. This makes chipless RFID much more cost-effective, particularly for large-scale applications. In addition, chipless RFID tags can be printed directly onto paper, plastic, or other materials, making them extremely versatile and easy to integrate into a wide range of products.

Several approaches to implementing chipless RFID include frequency modulation, time-domain reflectometry, and spectral signature techniques. Each of these approaches has its own advantages and disadvantages, and researchers continue to explore new approaches and refinements to existing techniques.
Overall, chipless RFID is a rapidly evolving field, with significant potential for impact across a wide range of applications. The development of smart chipless electronic labels represents an exciting new paradigm in the

field and promises to offer significant benefits in terms of cost, versatility, and functionality compared to existing chip-based RFID technologies.

The paper is structured as follows. In the next section, the approach used to carry out the whole LCA analysis is described. The theoretical underpinnings of our assumptions, system boundaries, Inventory analysis, data collection, process interpretation, and the LCA models developed for UHF RFID tags, Chipless tags, as well as barcode tags, are described in sections III, IV, and V respectively. Results and discussion are presented in Section VI. Section VII summarises the main conclusions of this study, discusses the limitations, and outlines future research activities.

2. Methodology

2.1. The methodological approach

Life cycle assessment (LCA) is a methodology used to evaluate the environmental impact of a product or technology throughout its life cycle. The life cycle of a product includes all stages from the extraction of raw materials, through manufacturing, transportation, use, and disposal. The goal of LCA is to identify and quantify the environmental impact of each stage of the life cycle, so that efforts can be made to reduce the impact.
To evaluate the environmental impact of RFID tags, chipless tags, and bar codes, the following steps are taken to conduct an LCA for these technologies:

- Goal and scope definition: In first step, the goal of the LCA and the scope of the analysis are defined. Throughout the paper, the main object is to compare the environmental impact of RFID tags, chipless tags, and bar codes to evaluate the benefits of applying the backscatter modulation technology in practice and its potential in the near future.
- Life cycle inventory: In this step, data on the materials and energy used at each stage of the life cycle are collected. This includes data on the raw materials used in manufacturing, energy used during production, transportation, use, and disposal. It is self-evident that to obtain meaningful results, the whole analysis should be focused on a defined, and hopefully real, implementation context, so as to build the LCA models starting from real data. As a matter of fact, analyzing a real scenario allows for retrieving realistic data concerning the manufacturing process and the transportation activities of these tags, as well as the overall product disposal process but that comes with a huge amount of documentation requirements along with the complex manufacturing processes of each product, especially for classic RFID tags with integrated electronic chips that go through hundreds of cycles and the use of thousands of chemicals and materials for production. In light of this consideration, in this study, we targeted a real implementation context by constructing a model LCA for three specific tags representing three technologies, they will be introduced in more detail in the next section.
- Life cycle impact assessment: The impact assessment phase aims to evaluate the potential environmental impacts of a system based on the data collected during the inventory analysis, including emissions, releases into the environment, and resource consumption (ISO 14040, 2006). This study only covers the classification and characterization stages of the impact assessment. The ILCD 2011 Midpoint impact assessment method, developed by PRe Consultant based on the ILCD Handbook (European Commission’s Joint Research Centre, 2010), was selected. This method includes categories such as climate change, ozone depletion, human toxicity cancer effects, and others. The recommended characterization models and associated characterization factors are classified as levels 1, 2, and 3, or interim, based on their quality. Level 1 is the highest quality, while interim is the lowest and considered the best among the analyzed methods, but not mature enough for recommendation. The ILCD midpoint method supports the correct use of characterization factors for impact assessment, as recommended in the ILCD guidance document (European Commission’s Joint Research Centre, 2011).
- Interpretation: finally, the results of the LCA are interpreted to identify areas for improvement. This may include identifying materials or processes with a high environmental impact and developing

strategies to reduce the impact. For the purpose of the study, the contribution rate of the microchip manufacturing process to the environmental impacts will be considered, thereby evaluating the benefits that chipless cards bring.

Since there are three types of tags, each of them has its own life cycle, the approach followed to assess the environmental sustainability of these technologies consists of four steps above for each one, as summarized in Fig. 1. The basic idea of the LCA analysis, which is carried out in this paper, is that the overall environmental impact of each kind of specific tags with the intention of assess the effect of microchip's manufacturing process and the benefits of chipless tag over a barcode and classic RFID tag. On the basis of this expectation, for each type of tag, we develop three different LCA models, by studying the entire life cycle from raw material production, production, use, and disposal of an actual product representing each process (UHF RFID, chipless RFID, and barcodes) then analyzes the environmental impact of each type and compares the results that the three models have produced.

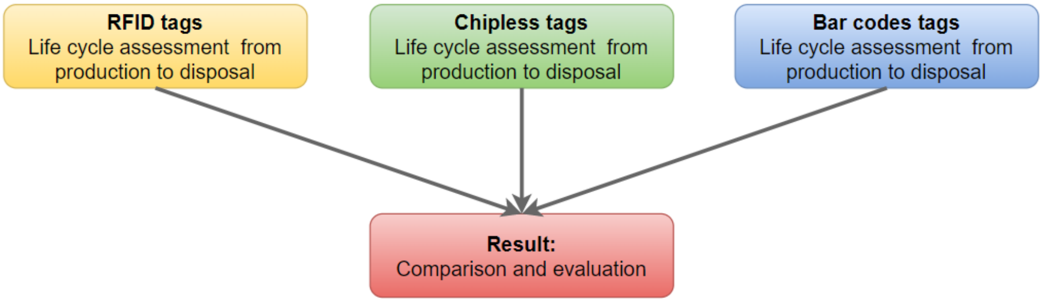


Figure 1. Approach adopted in the study

2.2. *Introduction to OpenLCA tool and Product Environmental Footprints (PEFs) database*

Modeling for the product lifecycle under evaluation, OpenLCA software, and the Product Environmental Footprints database (PEFs) be used.

OpenLCA is a widely used software tool for performing life cycle assessment (LCA) analyses. It is an open-source software developed by GreenDelta, and is available for free to download and use. OpenLCA allows users to model and analyze the environmental impacts of products or systems throughout their entire life cycle, from the extraction of raw materials to the end of life disposal. The software provides a comprehensive set of features for creating and modifying LCA models, including inventory data management, impact assessment methods, and reporting tools. OpenLCA also allows for the import and export of data in various formats, making it compatible with other LCA software tools and databases. Its user-friendly interface and extensive documentation make it a popular choice for both academic and industrial users.

The Product Environmental Footprints (PEFs) initiative originates from the European Commission's Single Market for Green Products initiative which proposed to look into the feasibility of an initiative on the Ecological Footprint of Products to address the issue of the environmental impact of products, including carbon emissions and explore possibilities for establishing a common European methodology to assess and label them.

Upon the publication of the Single Market for Green Products Initiative, the European Commission was invited by the European Council to develop a common methodology for the quantitative assessment of the environmental impacts of products, throughout their life-cycle, in order to support the assessment and labeling of products.

PEF results from a three-year multi-stakeholder testing period labeled the Environmental Footprint (EF) pilot phase which lasted from 2013 to 2016 (European Commission, 2018a). The methodology developed for PEF already began in 2011 with an analysis of existing methods. The investigated methods (i.e., BP X30, Ecological Footprint, GHG protocol, ILCD, ISO 14040-44, ISO 14025, PAS 2050, WRI/WBCSD) were

incorporated into a draft methodological guide for the calculation of the environmental footprint of products and organizations as well as into training programs.
The PEF Environmental Footprint (Mid-point indicator) LCIA method is included in the PEF database available on nexus.openLCA.org. It includes the impact categories: Global warming potential (GWP), Ozone depletion potential (ODP), Acidification potential (AP), Eutrophication potential (EP), Photochemical ozone creation potential (POCP), Human toxicity potential (HTP), Freshwater ecotoxicity potential (FETP), Marine ecotoxicity potential (METP), Particulate matter (PM) potential, Water depletion potential (WDP), Fossil fuel depletion potential (FFDP), Land use potential (LUP).

3. Life cycle assessment of chip tags

On the market today, there are many types of cards made based on UHF RFID technology with a variety of sizes, types and brands. Therefore, different types of RFID tags include different materials, rates, manufacturing processes, transportation operations, and disposal methods. To facilitate the construction of an LCA model representing the life cycle of a vintage card, the **"CCRR A61F 44 x 19mm Sticker Label"** is selected in this study. This is a simple passive tag manufactured by Beontag (www.beontag.com). This tag is designed with supply chain management in mind and is ideal for applications such as asset management, supply chains, inventory, logistics, boxes, and pallets. For the LCA analysis, primary data related to this product were provided directly by the manufacturing company.

3.1. *System boundaries and assumptions for RFID tag*

In order to obtain a comprehensive understanding of the environmental impact of RFID technology, it is necessary to consider all life cycle phases of the RFID tag. The LCA model developed for the RFID tag takes into account every stage of its life cycle, from the extraction of raw materials to the final disposal of the tag. This ensures that every aspect of the tag's environmental impact is thoroughly examined and evaluated.

To ensure that the analysis is manageable, a cut-off point of 1% of the total mass was adopted in this study. This means that any elements that make up less than 1% of the total mass of the tag will not be included in the analysis. However, it should be noted that this cut-off point is based on a judgement call, and the results of the analysis may have been different had a different cut-off point been used. Nonetheless, the use of a cut-off point is a common practice in LCA studies and helps to ensure that the analysis remains manageable while still providing meaningful results.

The life cycle of the RFID tag is a complex process that involves several phases, from the extraction of raw materials to the final disposal of the tag. The detailed analysis of each phase is essential to provide an accurate assessment of the environmental impact of the tag. Figure 2 presents a comprehensive view of the life cycle of the RFID tag, including all the phases considered in the analysis. The first life cycle process involves the extraction of raw materials necessary for the manufacturing of components such as antenna, chip, and inlay. The following phases focus on the manufacturing processes of these components and their assembly. Finally, the transportation of the tag from the production site to the deployment site, and its end-of-life management are examined to provide a complete picture of the life cycle.

It is important to note that the RFID reader's life cycle is not considered in this analysis since it falls within the cut-off value set. The reader's expected lifetime use involves reading thousands of tags, making its environmental impact concerning one tag negligible. The same applies to other equipment utilized in the supply chain to read the RFID tags, such as RFID gates. The high number of tags that equipment will read during its life cycle renders its environmental impact with respect to one tag of limited relevance. However, the focus on the RFID tag's complete life cycle provides a precise understanding of the tag's environmental impact, ensuring a reliable and accurate assessment.

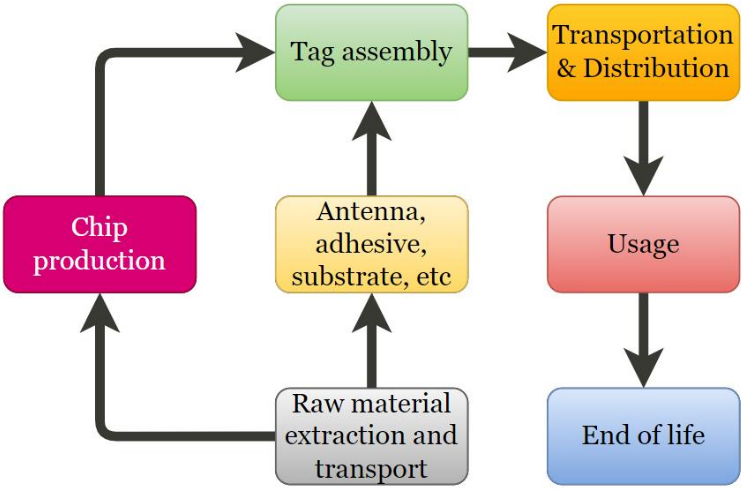


Figure 2. System boundary of RFID tag life cycle

3.2. *Inventory analysis and data collection for the RFID tag life cycle*

The life cycle inventory analysis quantifies the resource use, energy use, and environmental releases associated with the system being evaluated. In the following subsections, we detail the inventory analysis for the RFID tag life cycle.

3.2.1. *Manufacturing process of the RFID tag*

A common UHF RFID tag is a lamination of multiple layers. The first layer is made usually of paper or polypropylene and is a protective layer. The integrated circuit or chip (IC) is linked with the antenna through a conductive adhesive which can be an epoxy, tape, or a paste. ICs are created on a large semiconductor wafer and the ICs on each wafer need to be cut and separated and then attached to a tag antenna. Chip manufacturing involves hundreds of different stages and is carried out by a variety of machines and uses dozens of chemicals. The antenna is made of aluminum or copper and it is attached to a substrate of plastic (usually PET) or paper using the screen printing method. The last layer is the liner adhesive which is a silicone-coated paper and it has an acrylic adhesive layer to attach to the surfaces.

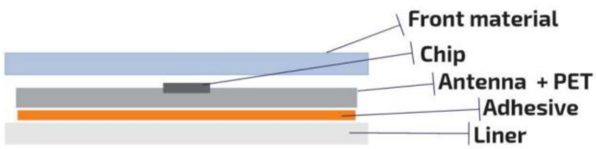


Figure 3. Structure of RFID tag

Table 1 provides a comprehensive overview of the various components that make up an RFID tag. This data was directly provided by the manufacturing company, Beontag, and includes detailed information about each component, including its related material and dimension. As can be observed from both Table 1 and Figure 1, an RFID tag is comprised of multiple parts. However, for operational purposes, there are two primary components that are of utmost importance: the chip and the antenna. The chip serves as the element that stores the tag information and is made from silicon and tetravalent metal-semiconductor. On the other hand, the antenna is constructed entirely from aluminum and is manufactured using the screen printing method. As mentioned, to join these two components together, adhesive layers made from acrylic and epoxy resins are used.

Table 1. Components of RFID tag

Components	Material	Description
Front material	White wood-free paper	101 µm
Back material	Liner	60g/m^2
Antenna material	Aluminum	10 µm on a PET 50 µm substrate
Adhesive	Acrylic and epoxy resins	Epoxy based material and Functional Permanent PSA Acrilyc
Microchip	95% silicon	Silicon, aluminum, nikel, tungsten, gold, etc

Apart from the detailed information provided in Table 1, the manufacturer has also given significant insights into the packaging of the RFID tags. This valuable information has been incorporated into Table 2, which illustrates the dimensions of each roll containing 5000 RFID tags packaged. The packaging of RFID tags plays a crucial role in the overall environmental impact of the product, as it can lead to increased transportation emissions, energy usage, and material waste. By providing information about the packaging, the manufacturer has enabled a more accurate assessment of the environmental impact of the product throughout its entire life cycle.

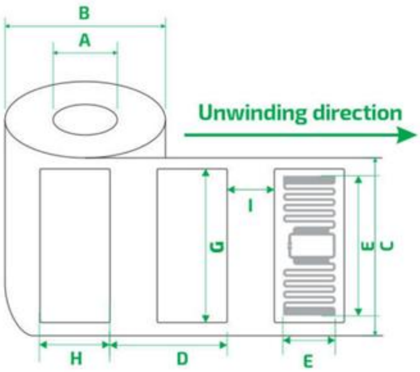


Figure 4. RFID tag packaging

Table 2. Dimension of RFID tag package

Dimension	item	Metric [mm]	Tolerance [mm]
A	Core inner diameter	76.2	2
B	Roll max outer diameter	203.2	5
C	Web width	50	1
D	Pitch length per piece (MD)	28.33	0.5
E	Antenna width	40	0.2
F	Antenna height	15	0.5
G	Die-cut width	44	0.5
H	Die-cut height	19	0.5
I	GAP	9.33	1
	Thickness	213 µm	13 µm

To ensure the accuracy of the LCA model for the RFID tag, it is necessary to determine the mass of each component used in its construction. This information can be obtained from the product datasheet provided by the manufacturer, which specifies the dimensions and fabrication material of each part. Based on this data, we can calculate the mass of each component, which will serve as input for the LCA model built in OpenLCA.

It should be noted that the accuracy of the LCA model is highly dependent on the accuracy of the input data. Therefore, it is crucial to carefully review the product datasheet and verify the mass of each component through direct measurement or additional data sources, if necessary. By accurately determining the mass of each component, we can ensure that the LCA model provides reliable results that can be used to make informed decisions about the environmental impact of the RFID tag throughout its entire life cycle. The dimensions of each component are indicated in Table 3.

Table 3. Components' attributes of RFID tag

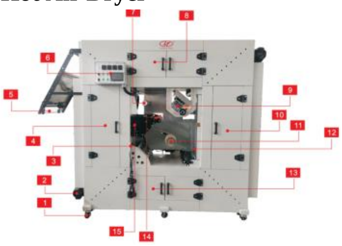
Number antenna per sheet	(500x700) / (55x28.33) = 224 pieces
Volume/antenna	15mm x 40mm x 0.01mm = 6mm^3
Mass/antenna (Aluminum)	6mm^3 x 2.7x10^{-3}g/mm^3 = 0.0162 g
Volume of PET substrate / sheet	800mm x 1100mm x 0.05mm = 44000mm^3 800mm x 1100mm = 880000mm^2
Volume of PET substrate / antenna	44000mm^3 / 224 pieces ≈ 196.43mm^3 880000mm^2/ 224 pieces ≈ 3928.57mm^2
Mass of PET substrate	196.43mm^3 x 1,38x10^{-3} g/mm^3 = 0.271g
Front material (white wood-free paper)	19mm x 44mm x 0.101mm = 84.436mm^3 19mm x 44mm x 150x10^{-6} g/mm^2 = 0.1254g
Liner	19mm x 44mm = 836 mm^2 836 mm^2 x 60x10^{-6}g/mm^2 = 0.05g
Adhesive	0.08g
Microchip	0.08 mg
Mass of tag	0.0162 + 0.271 + 0.1254 + 0.05 + 0.08E-3 + 0.08 = 0.5426g

In order to accurately evaluate the environmental impact of a product's manufacturing process, it is crucial to consider not only the materials used, but also the processes and methods employed. This is because the production process not only consumes materials, but also energy, water, and chemicals, which can all have environmental implications. As previously mentioned, the antennas used to manufacture RFID tags are made from aluminum using the screen printing method. However, information about the specific machinery used to make the CCRR A61F 44x19 mm Sticker Label was not available, so we conducted research on various types of screen printing machines on the market to gather data on the parameters of capacity, input materials, energy consumption, and other factors involved in the screen printing process used to produce RFID tags.

After careful consideration, we selected the screen printing machine LTA-5070, which is produced by Xiamen, China. This system consists of three main machine: powder machine, UV dryer, and roll to roll screen printing machine. Figure 5 and table 4 provide an overview image and detailed information on the parameters of this machine system. By gathering and analyzing this data, we can gain a better understanding of the environmental impact of the production process used to make the antenna of RFID tags.

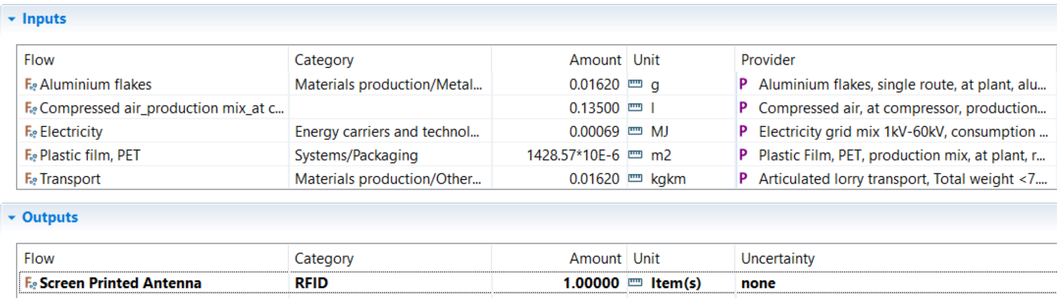
Figure 5. RFID Tag Antenna Screen Printer System, produced by Xiamen, China

Table 4. Data is provided by a vendor on the website

Specification		
Feeding Machine 	**Model**	LTC-600B
	Power	0.3 KW
	Electricity voltage	220V/50Hz
Screen Printing Machine 	**Model**	LTA-5070
	Screen Frame Area	800x1100mm
	Max. Printing Size	500x700mm
	Printing Speed	0~2500 pcs/hr.
	Main Drive Motor	0.75kw
	Pulling Drive Motor	1.5kw
	Air Suction Motor	0.3kw
	Supply Voltage	220V, 15A, 3KW
	Registration Accuracy	±0.01mm
	Air Source	0.4~0.6mpa
	Printing Material Thickness	0.02~0.5mm
Hot Air Dryer 	**Model**	LTB-600
	Power	22 KW
	Electricity voltage	380V/50Hz

According to Table 4, this machine has a printing speed of 0~2500 print/hour and with ours model parameter, we can print 224 antennas on a sheet. Assuming that the machine operates continuously, the machine can produce 224x2500 = 560000 antennas/hours.

Feeding Machine	0.3 kWh
Screen Printing Machine	3 kWh
Hot Air Dryer	22 kWh
Air Source	0.4~0.6mpa → 1.5kWh
Total	26.8 kWh
Electricity consumption per antenna	26800/560000 = 0.04786Wh = 1.7229x10^{-4} MJ


Inputs

Flow	Category	Amount	Unit	Provider
Aluminium flakes	Materials production/Metal...	0.01620	g	Aluminium flakes, single route, at plant, alu...
Compressed air_production mix_at c...		0.13500	l	Compressed air, at compressor, production...
Electricity	Energy carriers and technol...	0.00069	MJ	Electricity grid mix 1kV-60kV, consumption ...
Plastic film, PET	Systems/Packaging	1428.57*10E-6	m2	Plastic Film, PET, production mix, at plant, r...
Transport	Materials production/Other...	0.01620	kgkm	Articulated lorry transport, Total weight <7....

Outputs

Flow	Category	Amount	Unit	Uncertainty
Screen Printed Antenna	**RFID**	**1.00000**	**Item(s)**	**none**

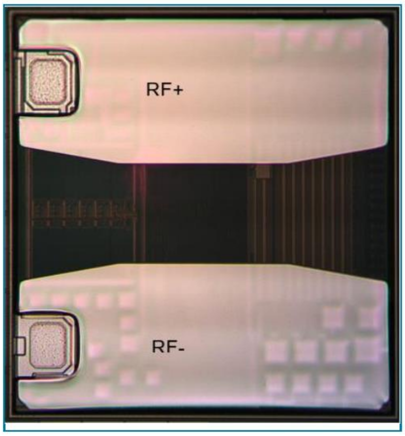
Figure 6. Use the application OpenLCA to create the manufacturing process of the antenna.

As mentioned, one of the two notable and significant environmental impacts in the manufacturing of RFID tags is the fabrication of printed antennas and microchips. While silicon, the primary component of the chip, is relatively benign to the environment, the chip manufacturing process involves a complex series of procedures that consume various chemicals and utilize diverse machines. For example, Silicon Wafer Manufacturing involves cutting silicon ingots into thin wafers, while Photolithography employs photoresist chemicals and exposure to light to pattern the wafer surface. The chemical composition of the chip includes not only silicon, but also several other elements such as aluminum, copper, and nitrogen. In our study, we focus on the CCRR A61F 44x 19mm Sticker Label product, which incorporates the IMPINJ MONZA 6 chip. To understand the environmental impact of this product, we need to develop a comprehensive model of the chip manufacturing process, taking into account the various chemicals, energy, and resource inputs required for each stage. With the datasheet of the chip and information about the mass and chemical composition of a single chip, we can build a more accurate and detailed model of the production process for the RFID tag. From the datasheet of this chip, we know a chip has a mass of 0.08 mg/die and has the same chemical composition as table 5.

Table 5. Material composition in The Monza R6 microchip
(features a 464.1 µm x 400 µm rectangular die size).

Incorporated Substances/Compounds	PPM
Silicon	>950000
Copper	<103000
Aluminum	<20000
Tungsten	<20000
Nickel	<40000

Titanium	<30000
Silicon Oxide	<5000
Silicon Nitride	<5000
Vanadium	<3000
Cobalt	**<20**
Arsenic	**<2**



Although the manufacturer does not provide comprehensive information on the entire chip manufacturing process, we can rely on the research paper "Environmental impacts of microchip manufacture" by Eric D. Williams for valuable insights. In this study, input parameters for the entire chip manufacturing process from a 1.6 cm2 wafer were collected, including the volume of chemicals used, gases such as N2, O2, H2, He, Ar, as well as electricity consumption and fossil fuels. However, it is important to note that the actual number of chemicals used in the process could range from tens to hundreds, as evidenced in the previous work of the author and collaborators, which provides a detailed breakdown of individual chemical usage. By leveraging this information, we can develop a more comprehensive and accurate model for the environmental impact assessment of RFID tags.

Table 6. Inputs to semiconductor fabrication

Material	Description	Amount per chip (1.6 cm^2 input silicon wafer)
Silicon wafer		0.25g
Chemicals	Dopants	0.016 g
	Photolithography	22 g
	Etchants	0.37 g
	Acids/bases	50 g
	Total chemicals	72 g
Elemental gases	N_2, O_2, H_2, He, Ar	700g
Energy	Electricity	1.6 MJ
	Direct fossil fuel	970 g
Water		32l

In the manufacturing process of microchips, the die is usually fabricated and cut from an 8 Inch Wafer and flip chip technology is used. To take advantage of the wafer production cycle available in the database and skip some of the initial steps in the wafer fabrication process, we propose to consider the production of chips from an 8-inch wafer. By calculating the area of one wafer, which is 100mm × 100mm × π = 104π mm2 = 0.0314 m2, we can estimate the number of chips per wafer, which is 104π mm2 / 0.36mm2 = 87266. However, considering the loss due to the cuts, the round shape of the wafer, and the failure rate, we assume that one wafer can produce around 80000 tag chips. This simplified calculation will allow us to estimate the environmental impact of producing the microchips used in the CCRR A61F 44x19mm Sticker Label product, based on the available data in the database.

Inputs

Flow	Category	Amount	Unit	Provider
Aluminium ingot	Materials production/Metal...	0.14000	g	P Aluminium ingot mix, productio...
arsenic	Resources from ground/No...	0.78500	g	
Cobalt, refined (metal); hydro- and ...	Materials production/Metal...	0.00014	g	P Cobalt, production mix, at plant...
Electricity	Energy carriers and technol...	2.90000	kWh	P Electricity mix for plastic proces...
Electricity	Energy carriers and technol...	112.84375	MJ	P Electricity mix for plastic proces...
Electricity from fossil unspecified	Energy carriers and technol...	78.50000	MJ	P Electricity from fossil unspecifie...
Electricity from fossil unspecified	Energy carriers and technol...	148.65938	kWh	P Electricity from fossil unspecifie...
Gold	Materials production/Metal...	0.05000	g	P Gold (primary route), productio...
Hydrochloric acid	Organic chemicals/nan	613.00000	g	P Hydrochloric acid production, p...
Nickel	Materials production/Metal...	1.50000	g	P Nickel, production mix, at plant,...
Nitric acid	Organic chemicals/nan	613.00000	g	P Nitric acid production, producti...
Silica (silicone dioxide); technology ...	Materials production/Inorg...	0.03500	g	P Silica (silicone dioxide), Product...
single-Si wafer, photovoltaics, at pla...	Materials production/Metal...	0.03140	m2	P RAW MAT PRE-PROC: single-Si...
single-Si wafer, photovoltaics, at reg...	Materials production/Metal...	0.03140	m2	P RAW MAT PRE-PROC: single-Si...
Sodium hydroxide	Organic chemicals/nan	1226.00000	g	P Sodium hydroxide production, ...
Sulphuric acid	Organic chemicals/nan	18.15312	g	P Sulphuric acid production, prod...
titanium	Resources from ground/No...	0.00028	g	
Transport	Materials production/Other...	800.00000	kgkm	P Articulated lorry transport, Total...
tungsten	Resources from ground/No...	0.14000	g	
Water, completely softened_technol...		1570.00000	kg	P Water, completely softened, at ...

Outputs

Flow	Category	Amount	Unit	Costs/Revenu...	Uncertainty
Chip	**RFID**	**8.00000E4**	**Item(s)**		**none**
Methyl chloride	Emissions to air/Emissions t...	1079.37500	g		none

Figure 7. Use the application OpenLCA to create the manufacturing process of the chip.

RFID tags are typically made using binders such as acrylic and epoxy resins. While the PEFs database provides information on the entire manufacturing process of epoxy, it does not have information on the production process of Functional Permanent PSA Acrylic. However, the database does provide information on the basic components required to synthesize acrylic resins. Therefore, it is possible to gather information on the production process of acrylic resins in order to build a model for producing them in OpenLCA.

To obtain information on the production process of acrylic resins, we referred to the PSA patent (https://patents.google.com/patent/US9518199B2/en). The patent describes a pressure-sensitive adhesive (PSA) polymer that is formed from a combination of different components. Specifically, the polymer is composed of (i) 50%- 95% by weight of n-butyl acrylate, (ii) 1%-20% by weight of ethyl acrylate, (iii) 1%-20% by weight of vinyl acetate, (iv) 0.1%-5% by weight of at least one ethylenically unsaturated acid or ethylenically unsaturated acid anhydride, and (v) 0% to 30% by weight of other ethylenically unsaturated compounds different from the monomers (i) to (iv). This PSA polymer is commonly used for producing self-adhesive articles such as paper or film labels.

Inputs

Flow	Category	Amount	Unit	Provider
2-ethylbutyric acid	Emissions to air/Emissions t...	0.00000	kg	
butyl acrylate	Organic chemicals/nan	0.95000	kg	P butyl acrylate production, producti...
ethyl acrylate	Emissions to air/Emissions t...	0.00000	kg	
Transport	Materials production/Other...	1000.00000	kgkm	P Articulated lorry transport, Total w...
Vinyl acetate ethylene dispersion; te...	Materials production/Orga...	0.02000	kg	P Vinyl acetate ethylene dispersion , ...

Outputs

Flow	Category	Amount	Unit	Uncertainty
Adhesive	**RFID**	**1.00000**	**kg**	**none**

Figure 8. Use the application OpenLCA to create the manufacturing process of the adhesive.

For the remaining main components Front material (white wood-free paper) and Back material (liner) the database that provides the manufacturing processes for them is respectively "Uncoated wood free paper, at plant, production mix, per kg wood free paper" and "Testliner (2015), production mix, at plant, technology mix, thermal energy sold/used externally, 1.09 kg waste paper input per kg Testliner". Besides the primary data shown in Table 1, some further secondary data were also retrieved from the PEFs database.

3.2.2. Transport activities

Considerations were made regarding transport activities for the production of the RFID tags. The antenna and chip are typically manufactured in China and are transported by air to the Beontag industrial park in Campo Mourão, Brazil, for assembly. This shipment covers an approximate distance of 18,000 km by plane from China to the Campo Mourao airport and 200 km by truck from the airport to the Beontagsan industrial park. For the remaining tag components, such as inlays, some suppliers located near the Beontag factory manufacture them, and a truck distance of about 200 km is considered for their shipment to the factory. The outbound transport of Beontag products worldwide is also considered, but for the purpose of this analysis, the focus is on a retail application in France. Thus, an average distance of 9,000 km by plane from Campo Mourão to Paris and 200 km by truck from the airport to the distribution center and two retail stores in the north of France is estimated for the tags to reach their deployment sites.

Transport activities	
Antenna and microchip	Plane: 18,000 km Truck: 200 km Plane: 9000km Truck: 200km
Another components	Truck: 200 km Plane: 9000km Truck: 200km

Screen Printed Antenna	RFID	1.00000	Item(s)	none	P Screen Pri...
Transport	Materials production/Other...	0.13630	kgkm	none	P Articulate...

Figure 9. Use the application OpenLCA to create the transport activities.

3.2.3. Usage activity and End of life of RFID tags

The end-of-life phase of a product can be simulated through the Material Flow Logic method, which models the natural direction of the material flow using waste streams. However, some databases, such as ecoinvent, do not support the use of waste streams. In such cases, the Opposite Direction Approach can be employed, which follows the opposite direction of the material flow. Fortunately, openLCA allows for both methods of waste modeling to be used.

Material Flow Logic involves modeling the waste treatment process, or end-of-life phase, by including a waste flow in the input table with a positive value. On the other hand, the waste generation process, or usage activity, is modeled by including a waste flow in the output table with a positive value.

The Opposite Direction Approach involves modeling the waste treatment process, or end-of-life phase of tags, by including a product flow in the output table with a negative value (logically an input). Similarly, the waste generation process, or tag usage, is modeled by including a product flow in the input table with a negative value (logically an output).

For simplicity, we choose Material Flow Logic method to build end-of-life and usage models for tags. Ignoring the process of separating the card components, we only consider the waste process of the materials used to produce the tags. Moreover, during usage activity, the energy consumption from reading tags is also neglected because even the cheapest reader from the manufacturer can be used for decades with a reading speed of up to 200tags/s.

The parameters of the weight, volume, or number of components of the tags are processed at the end of life based on the components that make up the tags that have been specified at the production stage.

Inputs

Flow	Category	Amount	Unit	Costs/Revenu...	Uncertainty	Avoided waste	Provider	Data quality ...	Description
RFID chip tag	RFID	1.00000	Item(s)		none		P RFID chip ...		

Outputs

Flow	Category	Amount	Unit	Costs/Revenu...	Uncertainty	Avoided pro...	Provider	Data quality ...	Description
RFID Chip tag disposed	**RFID**	**1.00000**	**Item(s)**		**none**				
Waste RFID Chip tag	RFID	0.13630	g		none		P Waste RFI...		

Figure 10. Use the application OpenLCA to create the Usage activity tags.

Inputs

Flow	Category	Amount	Unit	Costs/Revenu...	Uncertainty	Avoided waste	Provider	Data quality ...	Description
Transport	Materials production/Other...	0.13630	kgkm		none		P Articulate...		
Waste RFID Chip tag	**RFID**	**0.13630**	**g**		**none**				

Outputs

Flow	Category	Amount	Unit	Costs/Revenu...	Uncertainty	Avoided pro...	Provider	Data quality ...	Description
Aluminium_EoL	End-of-life treatment/Other...	0.01620	g		none	☑	P END-OF-L...		
Electronics scrap	End-of-life treatment	0.01000	g		none		P End of life...		
Incineration good	Wastes	0.07524	g		none		P Waste inci...		
Incineration good	Wastes	0.9*9.7857E-2	g		none		P Waste inci...		
Incineration good	Wastes	0.05016	g		none		P Polyamide...		
Polyethylene terephthalate (PET)	End-of-life treatment	9.7857E-2*0.1	g		none		P Polyethyle...		

Figure 11. Use the application OpenLCA to create the End of life of RFID tags.

4. Life cycle assessment of chipless tags

4.1. *Overview the chipless tags*

Chipless RFID tags are a promising technology that offers a number of advantages over conventional RFID tags. One of the biggest advantages is that chipless tags can be produced using printing techniques, which makes them much more cost-effective to manufacture. In fact, single-layer chipless tags can be printed directly onto a product, making them as affordable as optical barcodes. Another advantage of chipless RFID tags is their read range. Chipless tags can be read from a distance of up to one meter or more, which is comparable to the read range of conventional RFID tags. Additionally, chipless tags can be positioned on an object in a similar way to conventional RFID tags, making them easy to use and integrate into existing systems.

The principle behind chipless RFID tags is quite different from that of conventional RFID tags. Instead of using a silicon chip to store information, chipless tags rely on the scattering of metallic strips on the tag when they are hit by an electromagnetic wave. This scattering creates a unique electromagnetic signature that can be used to identify the tag. Some chipless tags use temporal analysis of the signature to extract and discriminate an ID, while others use spectral analysis to increase density of coding and miniaturization. While chipless RFID tags do not have the same coding capacity as conventional RFID tags, they do offer some benefits in terms of simplicity and cost-effectiveness. There is no need for a microelectronic manufacturing process or complex connection method between the antenna and the chip. This makes the tags more robust and less expensive to produce. However, one potential drawback of chipless RFID is that there is no collision management in chipless RFID, so it is not designed for simultaneous reading of many tags in the field. Nonetheless, techniques can be implemented to detect a few chipless tags at a time using temporal, spatial, or spectral separation methods.

Overall, chipless RFID tags offer a number of advantages over conventional RFID tags, particularly in terms of cost-effectiveness, read range, and ease of use. With the continued development of printing techniques and other production methods, it is likely that chipless RFID tags will become increasingly common in a variety of industries and applications.

4.2. *System boundaries and assumptions for chipless tag*

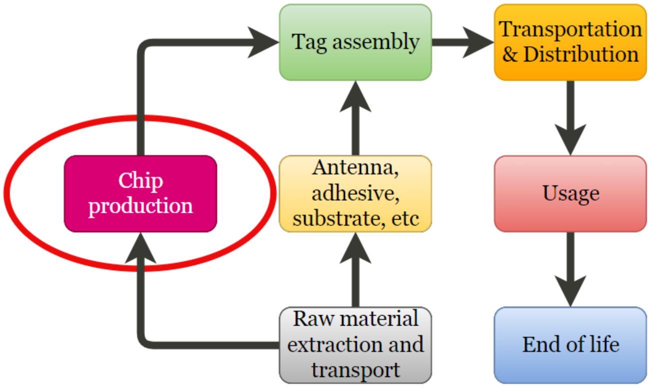


Figure 12. System boundary of chipless tag life cycle.

In order to fully comprehend the environmental impact of chipless technology, it's essential to consider all the life cycle phases of the chipless tag, similar to how system boundaries are set for RFID technology. To keep the analysis manageable, a 1% cut-off point of the total mass was established. The life cycle of a chipless tag is a complex process with several phases that should be thoroughly analyzed to provide an accurate assessment of its environmental impact. This analysis includes the extraction of raw materials needed for components such as the antenna and inlay, the manufacturing processes for these components, assembly, transportation from the production site to the deployment site, and end-of-life management. It's important to note that the manufacturing process of the microchip is not considered in the life cycle of chipless technology. In the same way as the case of RFID tags, it's worth noting that the reader's life cycle is not taken into account in this analysis, given that its impact is negligible concerning one tag. This is because readers are expected to read thousands of tags during their lifetime.

4.3. *Inventory analysis and data collection for the chipless tag life cycle*

4.3.1. *Manufacturing process of the RFID tag*

According to the author of "Design of Chipless RFID Tags Printed on Paper by Flexography", the use of flexography printing technology makes it easy to create chipless tags. In simpler cases, a single layer of metallic ink deposited on a substrate is sufficient. Printing tags on a paper substrate is considered the optimal achievement in the field of chipless technology. Flexography printing is capable of very high speeds, approximately 10 m^2/s, and achieving resolutions of 50 to 100 µm, which are compatible with various chipless tags. Additionally, an ink thickness of up to 5 µm can be deposited, making it ideal for RF circuits that require excellent conductivity. For mass production, flexography printing is considered the most appropriate technique for creating a large number of identical tags (with the same ID) in the initial stage. However, during the second stage of "configuration" to set a unique ID, other techniques like inkjet printing, laser, or mechanical cutting of conducting strips can be employed. A slot or conductive strip can be lengthened to modify the resonant frequency of a scatterer or remove a resonant frequency from the spectrum. As a result, a unique ID can be assigned to the tag later using a flexible and low-cost technique. The production cost of printed tags depends on the amount of conductive ink used, with the effective area of metallic conductors being 1 cm² for chipless tags based on Clike resonators.

However, as the author has stated, the Printable electronics industry will grow strongly in the future, considering the time of publication of the scientific paper is in 2013 and the data used is in 2012. At the moment, some settings will be changed to match the popular printing technology at the moment in order to objectively assess the impact of the life cycle of chipless tags. As mentioned above, the manufacturing process of chipless card antennas has to go through 2 stages, phase 1 is to produce tags with completely identical IDs. At this stage, instead of using flexography printing technology, we will replace it with screen printing technology like the technology used to make antennas for RFID tags. In phase 2 for the purpose of configuring to set a unique ID for each tag, we will consider inkjet printing for this study because this technology is being applied to be able to print RFID tags directly on paper instead of paper using plastic. Inkjet printing is a digital and non-contact technique that is almost free of chemical waste and doesn't require special facilities to be performed. Furthermore, the possibility of using well known substrates like paper or polymer films enables flexible, cheap and disposable devices. It is ideal for fast prototyping and promise high throughput, low cost and improved environment-friendliness. The main advantage of inkjet printing is its digital nature that allows every single printed drop and each pattern to be independent of the previous one. This means a high control over the process and no changeover costs if the same ink is used, making inkjet printing the cheapest printing technique for low volumes and thus it is often used in research. Furthermore, it is easily scalable using the same print head mounted on a larger stage or using multiple print heads.

As for the size and material specifications, each part of chipless tags such as the substrate or antenna will be kept the same as Vena's research to ensure the functionality of the tags. However, for commercial products, a tag needs a protective outer shell, not just the substrate and antenna printed above, here we use the same cover material as the RFID tag. Table … provides a comprehensive overview of the various components that make up a chipless tag.

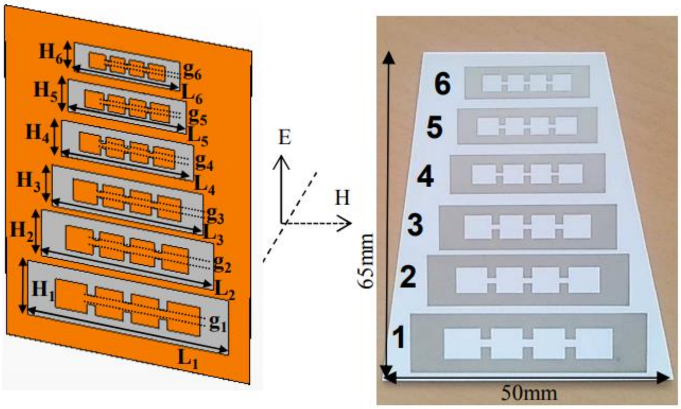


Figure 13. The tag printed on glossy paper by flexography

Table 7. Components of chipless tag

Components	Material	Description
Antenna material	Copper/ silver	5 µm (thickness)
Adhesive	Acrylic and epoxy resins	Epoxy based material and Functional Permanent PSA Acrilyc

substrate	Coated paper	0.22mm / 120 µm (thickness), 150 g/m^2

Table 8. Dimensions in mm of the tag based on 3-gap loop resonators

Res	1	2	3	4	5	6
L	49.4	42.1	37	32.2	28.9	25.7
H	12.4	10.6	9.3	8.1	7.3	6.5
g	2	1.3	1.1	1	0.9	0.8

From the dimensions and fabrication materials collected from Vena's research, we can calculate the volume as well as the mass of materials used relatively. The specific calculation is presented in the table 9.

Table 9. Components' weight of chipless tag

RFID tag dimension	
Antenna dimension	
Number antenna per sheet	(500x700) / (50x60) = 116 pieces
Area/antenna	(49.4 x 12.4) + (42.1x10.6) + (37x9.3) + (32.2x8.1) + (28.9x7.3) + (25.7x6.5) = 2041.76 mm^2
Volume/antenna	2041.76 mm^2 x 0.005 mm =10.2088 mm^3
Mass/antenna (copper)	10.2088 mm^3 x 8.96x10^{-3} g/mm^3 = 0.092 g
Volume of paper substrate / sheet	800mm x 1100mm x 0.22mm = 193600mm^3 800mm x 1100mm = 880000mm^2
Volume of paper substrate / antenna	193600mm^3/ 116 pieces ≈ 1668.97 mm^3 880000mm^2/ 116 pieces ≈ 7586.2 mm^2
Mass of paper substrate / antenna	7586.2 mm^2 x 150 x 10^{-6} g/mm^2 = 1.138 g
Adhesive	0.08g
Mass of tag	0.92 + 1.138 + 0.08 = 2.138 g

As said in the previous part, we will use the screen printing machine LTA-5070 for the first phase of chipless tag antenna fabrication. According to the datasheet of printing machine, we can produce 116 pieces/800x1100mm sheet.

Feeding Machine	0.3 kWh
Screen Printing Machine	3 kWh
Hot Air Dryer	22 kWh
Air Source	0.4~0.6mpa → 1.5kWh
Total	26.8 kWh
Electricity consumption per antenna	268000/(116x2500) = 0.0924Wh = 3.33x10^{-4} MJ

Inputs

Flow	Category	Amount	Unit	Provider
Compressed air_production mix_at ...		0.13500	l	Compressed air, at compre...
Copper (99.999%; electrolyte coppe...	Materials production/Meta...	0.91471	g	Recycling of copper from ...
Electricity	Energy carriers and technol...	0.00069	MJ	Electricity grid mix 1kV-60...
Transport	Materials production/Othe...	0.01620	kgkm	Articulated lorry transport, ...
Uncoated wood free paper_produc...		0.40000	g	Uncoated wood free paper...

Outputs

Flow	Category	Amount	Unit	Costs/Reven...	Uncertainty
Screen Printed Antenna	**RFID**	**1.00000**	**Item(s)**		**none**

Figure 14. Use the application OpenLCA to create the manufacturing process of the antenna of chipless tag.

As mentioned in stage 2, we will use the inkjet printing method to fine-tune the shape of the antenna to configure the chipless tag. Inkjet printing requires the functional material to be in a liquid form with restrictions on the viscosity and surface tension. To form a layer after printing, the material needs to contain or be converted to a solid material. The percentage of functional material in the ink controls the layer thickness of a single print and the number of printing cycles to achieve the desired thickness. The values are typically given as the solid loading, the ratio of the weight of functional materials to the weight of the ink. Common metal nanoparticle inks have solid loadings between 20 wt % and 60 wt %. The silver (Ag) nanoparticle ink were used to print a set of prototype. In this paper, a low-cost consumer inkjet printer, the Workforce 2010W by Epson, was chosen without further modification for the printing of the configuration. Since the print resolution was not an issue due to the width of the antenna's arms and the substrates were flexible enough to be bent in the paper feed, a high-resolution printer was not necessary, enabling the advantage of a faster printing speed. After printing, the samples were dried for 30 min at 60∘ in an oven.

Figure 15. Gold NP samples being printed with the Epson 2010W printer.

4.3.2. Transport activities

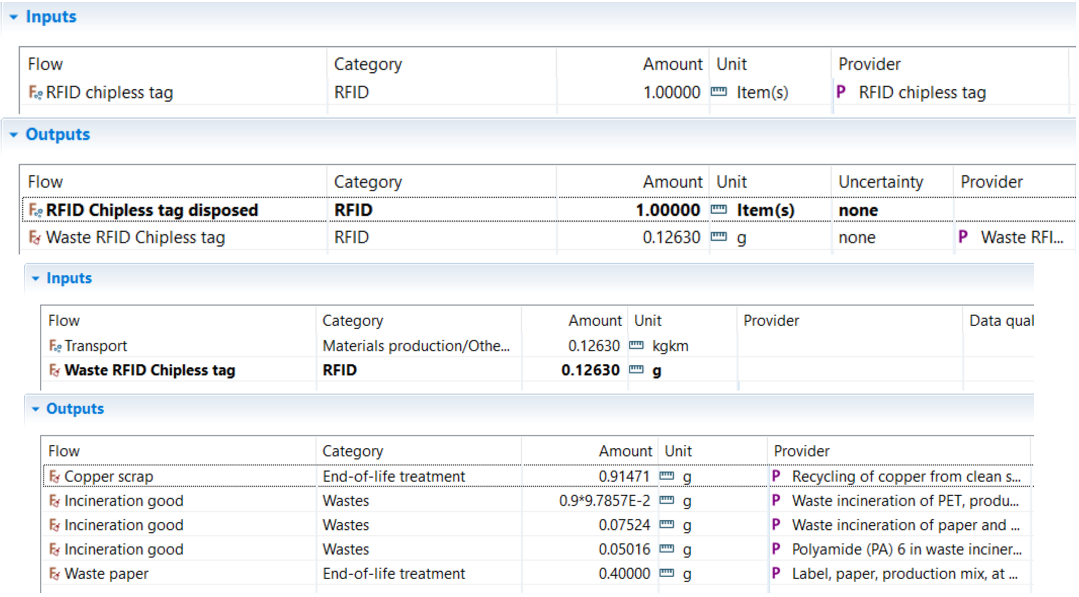
Assumptions about shipping operations for RFID tags will be considered for chipless tags, we only need to modify shipping volumes because chipless tags are on average larger and bulkier than their counterparts regular card.

Screen Printed Antenna	RFID	Item(s)	Chipless Antenna
Transport	Materials production/Othe...	kgkm	Articulated lorry transport, Total weigh...

Figure 16. Use the application OpenLCA to create the manufacturing process of the transport activities

4.3.3. Usage activity and End of life of chipless tags

There is no difference in approach for Usage activity and End of life of RFID tags, In line with this case, the parameters of the weight, volume, or number of components of the tags are processed at the end of life based on the components that make up the tags that have been specified at the production stage.



Inputs

Flow	Category	Amount	Unit	Provider
RFID chipless tag	RFID	1.00000	Item(s)	P RFID chipless tag

Outputs

Flow	Category	Amount	Unit	Uncertainty	Provider
RFID Chipless tag disposed	**RFID**	**1.00000**	**Item(s)**	**none**	
Waste RFID Chipless tag	RFID	0.12630	g	none	P Waste RFI...

Inputs

Flow	Category	Amount	Unit	Provider	Data qual
Transport	Materials production/Othe...	0.12630	kgkm		
Waste RFID Chipless tag	**RFID**	**0.12630**	**g**		

Outputs

Flow	Category	Amount	Unit	Provider
Copper scrap	End-of-life treatment	0.91471	g	P Recycling of copper from clean s...
Incineration good	Wastes	0.9*9.7857E-2	g	P Waste incineration of PET, produ...
Incineration good	Wastes	0.07524	g	P Waste incineration of paper and ...
Incineration good	Wastes	0.05016	g	P Polyamide (PA) 6 in waste inciner...
Waste paper	End-of-life treatment	0.40000	g	P Label, paper, production mix, at ...

Figure 17. Use the application OpenLCA to create the Usage activity and End of life of chipless tags.

5. Life cycle assessment of barcode tags

Barcode technology is a ubiquitous and cost-effective way to track products, inventory, and shipments in a warehouse. Barcodes are a series of parallel lines of varying thicknesses and spaces, which represent a code that is scanned by a barcode reader. While barcode technology has been around for several decades, it is still a widely used technology in many industries. However, with the advent of newer technologies like RFID and chipless tags, some organizations are considering making a shift to these more advanced technologies.

5.1. *System boundaries and assumptions for barcode*

Similar to the two technologies mentioned, a cut-off point of 1% of the total mass was adopted for the life cycle assessment of the barcode technology. The entire life cycle of the barcode label will be build as completely as possible and based on the popular one having the dimension of 30mmx50mmx172μm.

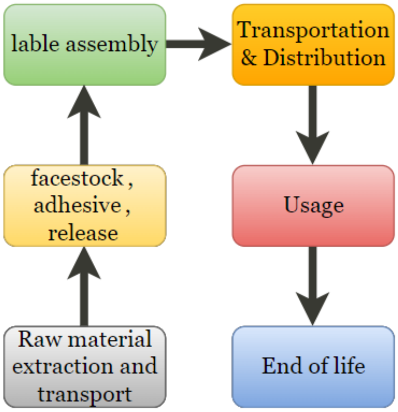


Figure 18. System boundary of barcode label life cycle.

5.2. *Inventory analysis and data collection for the barcode*

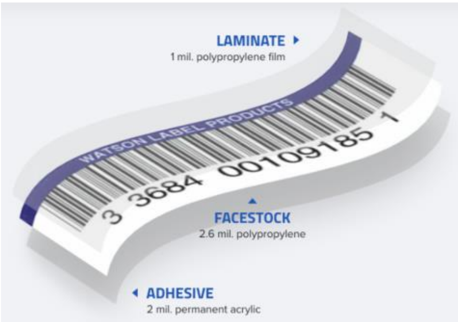


Figure 19. Principal components of a barcode label.

Labels generally consist of three basic parts:

- The **facestock** of a barcode label is the topmost layer that receives the printing or marking of the barcode image. It is usually made of paper, synthetic material, or a combination of both, and it must be able to receive the image in a clear and accurate manner to ensure reliable scanning. The facestock must also withstand environmental factors, such as temperature, humidity, and sunlight, to ensure that the barcode remains legible throughout its useful life. The facestock material is typically made using printing technologies such as flexography or digital printing. These technologies allow for high-quality printing of barcodes, text, and images on various types of materials.

- The **adhesive** layer is the layer that allows the barcode label to adhere to the surface of the item being labeled. The adhesive must be strong enough to hold the label securely in place, yet not so strong that it damages the item if the label is removed. The type of adhesive used can vary depending on the surface being labeled and the intended use of the label.

- The **release liner** is the bottommost layer of the barcode label and is designed to protect the adhesive layer until the label is ready to be applied. It is usually made of a non-stick material, such as siliconized paper, that allows for easy removal of the liner without damaging the adhesive. The release liner is removed from the label before application, and the label is then affixed to the item being labeled.

The manufacturing process of a barcode label typically involves the following steps:

- Design: The label design is created using computer software that allows for the inclusion of the barcode, company logo, text, and other important information.

- Material selection: The appropriate facestock, adhesive, and release liner materials are selected based on the specific application and environmental conditions.
- Printing: The label design is printed onto the facestock material using a printing method such as thermal transfer or direct thermal printing.
- Coating: The printed facestock material is coated with the appropriate adhesive to ensure proper adhesion to the substrate.
- Lamination: If necessary, a protective laminate layer may be applied to the label to provide additional durability and resistance to harsh environments.
- Die-cutting: The label is die-cut into the desired shape and size.
- Packaging: The finished barcode labels are packaged and shipped to the customer.

The barcode label manufacturing process is very simple and the modeling of the stages in OpenLCA is straightforward. Assumptions about Transport activities, Usage activity and End of life of chipless tags are built in the same way as RFID tags and chipless tags.

Table 10. Components of barcode label

Components	**Material**	**Description**
Facestock	Polyester	172 µm
Release liner	Polyester	172 µm
Adhesive	Acrylic and epoxy resins	Epoxy based material and Functional Permanent PSA Acrilyc

Normally, barcode labels are printed by flexography technology, here we will choose the DY-FLP650/2-A 2-color Flexographic printing machine manufactured by DaYuan Industrial Co., Ltd. We chose this because it has the same capacity and productivity as the screen printing machine selected for the two previous technologies.

Table 11. Data is provided by a vendor on the website https://xmlingtie.en.made-in-china.com/

Voltage	380V/50Hz
Power	38KW
Max Speed	200m/min
Max Roll Diameter	1200mm
Max Roll Width	650mm
Materials	100-380gsm （Aluminum foil coated paper, white cow card...）
Max Printing Width	650mm

Table 12. Components' weight of barcode label.

Barcode label dimension	
Number labels per min	80000 pieces
Volume/label	30mm x 50mm x 160µm = 240mm^3
mass/label	240mm^3 x 1.38x10^{-3}g/mm^3 = 0.331 g
Adhensive	30mm x 50mm x 10µm x 1.05x10^{-3}g/mm^3 = 0.01575 g

6. Results and contributions.

Considering the chip tags manufacturing model, in most environmental impacts, chip manufacturing processes always account for a large proportion indicating that the transition to the production and use of chipless tags is expected to explode in the future is doable.

In this section, we assess the impacts that arise as a result of the classical RFID tags. We start by discussing the outcomes from the LCA models and the environmental burden generated by the manufacturing activities of one RFID tag. Table 13 shows the results of the impact assessment of one RFID tag, according to the ILCD method. Those values represent the environmental burden caused by the life cycle of each tag. The same results are illustrated graphically in Fig.19, and Fig.20, where we also highlight the contribution of each component of the RFID tag to the overall environmental impact of the tag. As can be seen in Fig. 20, the manufacturing of the microchip has, by far, the highest environmental impact among all the categories. Its contribution ranges from 30% to 90%, with an average contribution of 74%. The impact of antenna manufacturing is also quite significant, ranging between 10% and 50% in all categories, with an average contribution of 33%. The remaining processes generate an overall contribution lower than 10% of the total impact.

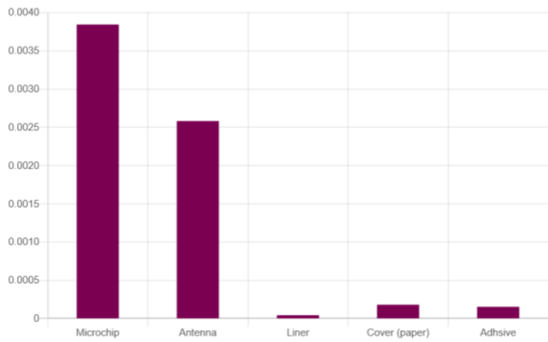


Figure 20. Greenhouse emissions of the components manufacturing process (kg CO2).

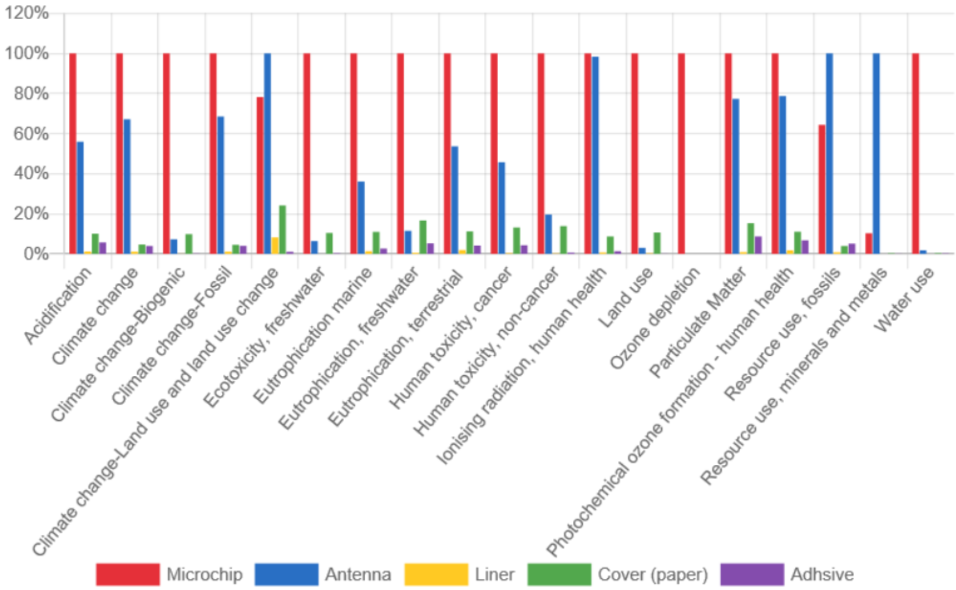


Figure 21. Entire environmental impacts of the components manufacturing process (kg CO2).

For the chipless tags sample manufactured in [1], the conductive strip is copper instead of aluminum to achieve the necessary conductivity. Moreover, the size of chipless tag is larger and the cover density of conductive ink is higher to ensure its function. In an identification application, each tag needs a unique ID, the tags should have different shapes, therefore the antenna need two phase to complete. However, the chip's production consumes plenty of energy as well as chemical and emits large amounts of greenhouse gases into the environment, so that the result of the comparison of the entire life cycles representing the manufacturing process, usage, and disposal of two tag types still matches the expectation, the replacement of the chip tags with chipless tags helps reduce environmental pollution.

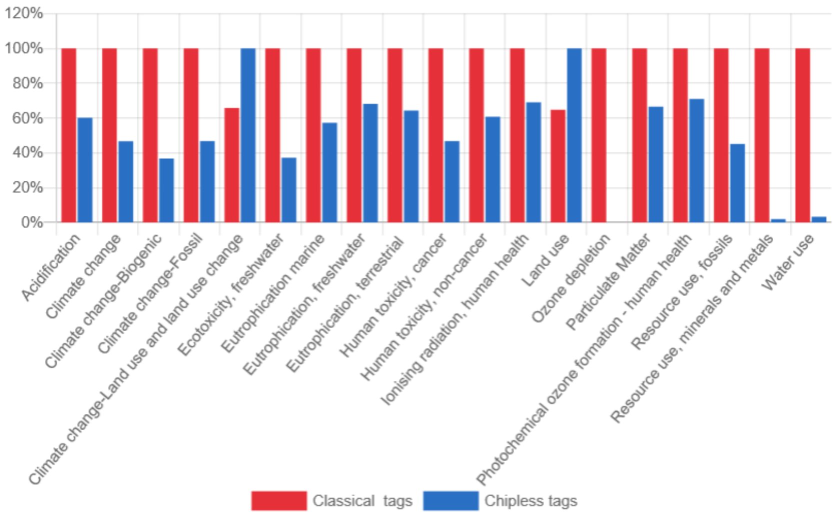


Figure 22. Comparison of environmental impacts of chip tag and chipless tag.

Indicator	Chip	Chipless	Barcode	Unit
Acidification	2.47905e-5	1.49018e-5	9.88254e-7	mol H+ eq
Climate change	8.13839e-3	3.79495e-3	2.04752e-4	kg CO2 eq
Climate change-Biogenic	1.61464e-4	5.93495e-5	3.67171e-7	kg CO2 eq
Climate change-Fossil	7.97174e-3	3.72772e-3	2.03189e-4	kg CO2 eq
Climate change-Land use and land use change	5.17873e-6	7.87519e-6	1.19586e-6	kg CO2 eq
Ecotoxicity, freshwater	3.38785e-2	1.25874e-2	6.26453e-5	CTUe
Eutrophication marine	9.37375e-6	5.36902e-6	3.37696e-7	kg N eq
Eutrophication, freshwater	2.63711e-7	1.79685e-7	5.71830e-9	kg P eq
Eutrophication, terrestrial	6.98971e-5	4.49642e-5	3.53710e-6	mol N eq
Human toxicity, cancer	9.12150e-11	4.26527e-11	2.62908e-12	CTUh
Human toxicity, non-cancer	2.02528e-9	1.23036e-9	2.32687e-11	CTUh
Ionising radiation, human health	5.99736e-4	4.13858e-4	1.82066e-5	kBq U-235 eq
Land use	4.53850e-1	7.00884e-1	3.46278e-3	Pt
Ozone depletion	2.02450e-7	3.03406e-11	6.10578e-14	kg CFC11 eq
Particulate Matter	2.74348e-10	1.82513e-10	9.38545e-12	disease inc.
Photochemical ozone formation - human health	1.60520e-5	1.13941e-5	9.86236e-7	kg NMVOC eq
Resource use, fossils	1.22313e-1	5.51820e-2	7.44519e-3	MJ
Resource use, minerals and metals	4.84390e-7	9.32006e-9	5.53938e-10	kg Sb eq
Water use	4.43825e-2	1.45121e-3	1.29051e-4	m3 depriv.

Table 13. Entire Environmental impact of chipless, RFID, and barcode technology.

Considering Table 13, it is not surprising that the impact of a barcode label is very small compared to the other two technologies, which can be seen more clearly in the graphs in Figures 22 and 23. Considering the two main technologies that need to be compared are RFID technology and Chipless technology, it can be seen that most of the environmental impacts caused by classical tags are always higher than the rest. This is understandable when we have assessed that the emission rate of microchips is the largest of the components that make up the RFID tag base. However, due to the larger size of Chipless tags and the use of copper for printing to ensure electrical conductivity as well as an additional ID configuration process, the impact of chipless technology on land use is higher, but insignificant compared to conventional technology.

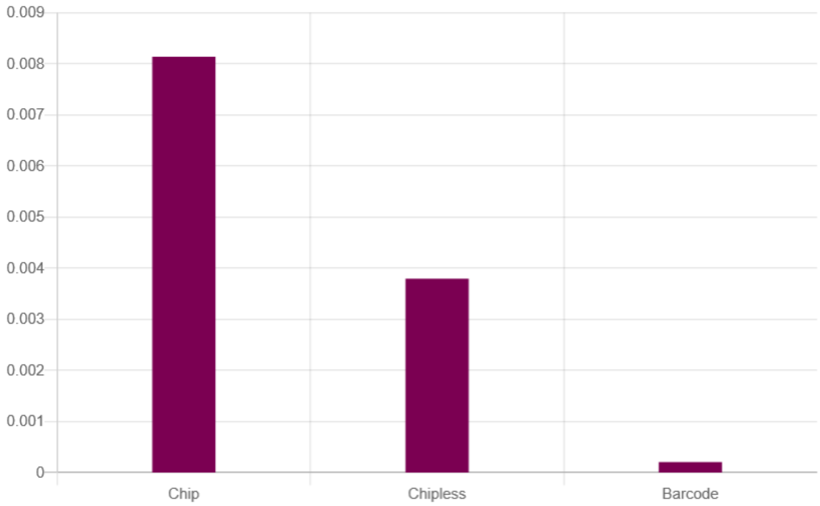


Figure 23. Greenhouse emissions of three manufacturing processes (kg CO2).

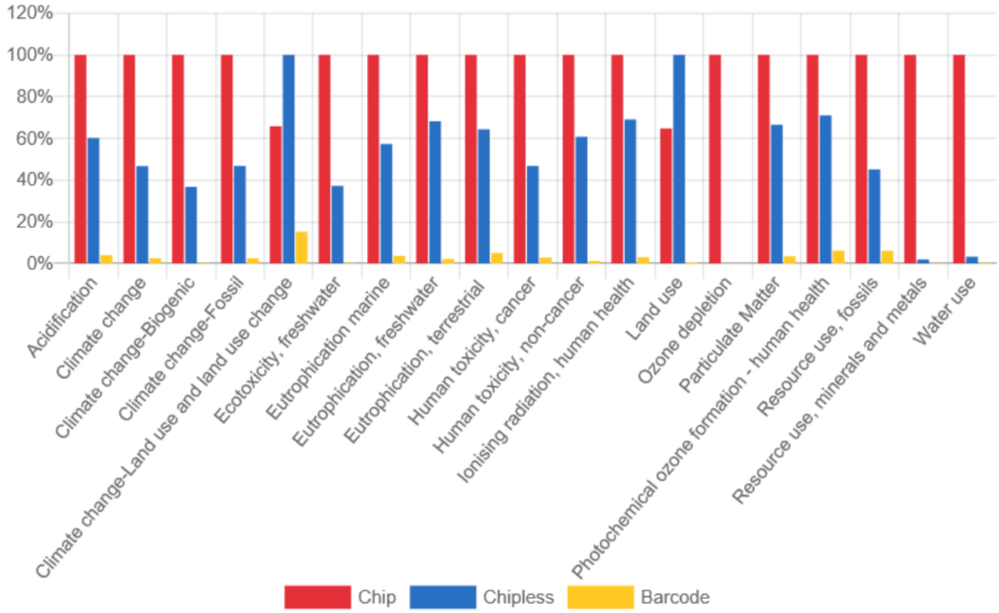


Figure 24. Comparison of environmental impacts of chip tag, chipless tag, and barcode label.

7. Conclusion

The objective of this work is to carry out a Life Cycle Assessment of: UHF RFID, chipless RFID, and barcodes and make a comparison between these different technological approaches. Although the usage data is not completely accurate, through this paper we can generalize that the impact on the environment during the production and use of RFID tags is significantly larger, while for barcodes technology the environmental impact is small but difficult to compare because of its functional limitations compared to the other two technologies. Therefore, this result demonstrates the potential of chipless RFID technology that should represent a very good choice for identification applications in the years to come.

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