NATIONAL UNIVERSITY OF SCIENCE AND

TECHNOLOGY POLITEHNICA BUCHAREST

DOCTORAL SCHOOL OF ELECTRICAL ENGINEERING

# DOCTORAL SUMMERY

## PHD THESIS – SUMMARY

## ENVIRONMENTAL IMPACT PRODUCED BY

## ELECTRICAL AND ELECTRONIC WASTE

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# CONTENT



Keywords: waste, electrical and electronic equipment, collection, recycling, circular economy

## Theme and purpose of the work

The doctoral thesis entitled “Environmental impact produced by electrical and electronic waste” is part of current research concerns. The goal of the doctoral thesis is to develop an easy-to-apply tool that can realize the annual forecast for the amount of waste that is intended to be collected.

The thesis was developed within the Faculty of Electrical Engineering of the National University of Science and Technology Politehnica Bucharest and contains original contributions in the field of how to report the amount of waste from electrical and electronic equipment.

## Paper structure

The thesis is structured on nine chapters and annexes and has a total number of 158 pages written in 1 row. The thesis also includes 89 tables and 34 figures. At the end of the paper are presented 55 bibliographic references in the order of their quotation in the text.

The first part of the thesis (chapter 1 to chapter 4) presents the current situation and the need to develop a reporting tool regarding the amount of electrical and electronic equipment placed on the market or for waste from electrical and electronic equipment collected.

The second part of the thesis (chapter 5 to chapter 9) is structured in four directions: presentation of the European reporting model, presentation of the developed instrument based on the Markov chain, the application of the instrument developed for the period 2022-2032 for both the quantity of electrical and electronic equipment placed on the market and the amount of waste collected from electrical and electronic equipment, integration of the model developed in the European model and the added value of the instrument with the related conclusions.

The last part of the thesis includes annexes and bibliography. The annexes are four: Annex 1 - Centralisation of information on electrical and electronic equipment placed on the market in the period 2024-2032, Annex 2 - Centralisation of information on waste from electrical and electronic equipment collected in the period 2024-2032, Annex 3 - List of tables and Annex 4 - List of figures.

## The current state of knowledge

Chapter I “ The current state of knowledge” presents the current situation with regard to electrical and electronic equipment placed on the market (EEEs) and waste collected from these equipment (WEEE). Every year, millions of EEE become waste as their lifespan is completed. If not properly recycled, treated, and disposed of, these equipment can become a threat to the environment and human health.

The increase in the production of goods and consumption has led to a major waste generation problem that will become one of the major challenges of contemporary society. In the context of this acute increase in the amount of waste from electrical and electronic equipment, many international organizations have allocated funding to carry out analyses and strategies to develop sustained instruments to increase the collection and recycling of this type of waste.

The European Union, through Directive 2002/96/EC, has imposed on member states to reach a target of collecting 4 kg of WEEE from households, per capita until 31 December 2006 [9]. The new 2012 Directive includes several important and fundamental changes to collection targets for all Member States. Thus, the collection targets are linked to the specific market conditions in each member state. After an initial transition period, the member state will be able to opt for expressing the collection target in the form of "percentage of the average amount of EEE placed on the market over the last 3 years” or "percentage of WEEE generated".

By the WEEE Directive (2012/19/EU), which entered into force on 13 August 2012, new targets have been introduced to increase collection in terms of the amount of waste from collected electrical and electronic equipment.

Consistent with the derogation provided for in Article 7, point 3, of the WEEE Directive, there were ten European Union member states that could decide to postpone the achievement of the collection target until 14 August 2021. These states were: Bulgaria, Czech Republic, Latvia, Lithuania, Hungary, Malta, Poland, Romania, Slovenia, and Slovakia.

Within "Report on the state of the environment in Romania", a report for 2022, developed by the National Agency for Environmental Protection, preliminary data on the amount of WEEE collected in 2021 were 89,510.172 tons.

The minimum WEEE collection targets under national legislation developed on the basis of European legislation varied by period, thus [3,4,9]:

- for the period 2008 - 2015, 4 kg waste/inhabitant/year;
- for 2016, at least 40% of the average quantity of EEE placed on the market over the last 3 years;
- in the period 2017 – 2020, 45% of the average quantities of EEE placed on the market in the last 3 years;
- since 2021, 65% of the average quantities of EEE placed on the market over the last 3 years;

## Recycling technologies

Chapter II "Recycling technologies" showcases current technologies for recycling metals/non-metals from electrical and electronic waste and emphasizes the economic value, on the reduced environmental impact and their marketing power.

Waste recycling techniques or treatment methods may be classified as:

a. Conventional recycling technologies (including direct treatment - storage and incineration, physical-mechanical and chemical separation);
b. advanced recycling technologies (including pyrometallurgy, hydrometallurgy, biometallurgy, electrometallurgy, vacuum metallurgy, supercritical fluids, full recovery of non-metallic fraction, etc.).

## The influence of electrical and electronic equipment on the environment

Chapter III "Influence of electrical and electronic equipment on the environment" presents the environmental impact of electrical and electronic equipment both in the manufacturing process, including, as well as in the marketing of electrical and electronic equipment, recovery and recycling of waste from such equipment. Thus, in this chapter, we have analyzed the tools that can be applied to reduce the impact on the environment.

Implementation of an environmental management system (EMS) by the requirements of ISO 14001:2015 in companies either producing or marketing these products, is an effective tool in the management of the organization. Other international standards that lead to the management of elements that have an impact on the environment and that occur both in the production of electrical and electronic products and in the marketing process and thereafter collection and recycling are the standards that show the guidelines for greenhouse gases. These standards are: "ISO14064-1 "Greenhouse gases Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals" and "ISO14064-3 Greenhouse gases — Part 3: Specification with guidance for the verification and validation of greenhouse gas statements". The reference document that follows the same direction is also the GHG Protocol.

## Operational management of electrical and electronic equipment

Chapter IV. “The operational management of electrical and electronic equipment management” presents the concept of circular economy in the context of waste recycling and recovery of reusable components from electrical and electronic waste. Thus, emphasis was placed on the need to develop a sustainable process in terms of a sustainable circular economy.

Replacing the traditional economic development model with the circular economy implicitly leads to the need to develop sustainable and manageable systems. The transition from a traditional economy that emphasizes resource consumption and waste generation to a sustainable economy requires effort from all countries of the world. A unitary approach is also needed for the waste industry from electrical and electronic equipment, as these types of waste contain toxic substances and precious metals.

The circular economy has received increasing attention from global decision-makers, as a concept that can support the objectives of reducing the excessive consumption of natural resources while providing economic benefits [36].

## Tools used to estimate the degree of collection of electrical and electronic equipment

Chapter V. “Tools used to estimate the degree of collection of electrical and electronic equipment” address Implementing Regulation (EU) 2017/699 Of 18 April 2017 establishing a common methodology for calculating the quantity of electrical and electronic equipment placed on the market of each Member State [39].

Of the need to implement Directive 2012/19/EU under the best possible conditions and in accordance with its implementing regulation, The European Commission has provided member states with a common tool for calculating the amount of electrical and electronic waste put on the market, an instrument found for each Member State on the European Union website [3, 39,40].

Like any tool, the one previously presented can be improved. A realistic forecast of the quantity of electrical and electronic equipment placed on the market can lead to the development of a methodology that can be easier to apply.

In Romania, there are serious problems regarding the degree of collection and, implicitly, the recycling of waste from electrical and electronic equipment. These problems are determined by the challenges faced by the Romanian market. Thus, it is not possible to calculate a clear collection target because not in all cases of acquisition of new electrical and electronic equipment is carried out and disposal of old ones, the existence of large stocks of electrical and electronic equipment in households, and not least the fact that old electrical and electronic equipment are often resold or ceded. In this respect, all the developed methodologies were based mostly on data collected from the sale of electrical and electronic equipment.

## Development of a calculation methodology on the degree of collection and recycling of electrical and electronic equipment

Chapter VI. “Development of a calculation methodology on the degree of collection and recycling of electrical and electronic equipment“, presents in the first part the mathematical tool developed based on Markov processes and later the application of this mathematical tool.

- Development of a mathematical tool for calculating the degree of collection and recycling of electrical and electronic equipment

The notion of chain in the current sense indicates a continuity, chaining, or a sequence of states. This notion is also used in consideration of a sequence of random states or independent stochastic events, which shows that the chain represents a series of random variables.

So, the proposed mathematical model is based on the development of a transition probability matrix that will be used to provide probability estimates of the quantity in each category of electrical and electronic equipment put on the market or waste from electrical and electronic equipment collected.

Applying the Markov model and starting from the hypothesis that there is a Markov decision process, which develops in n stages, and decisions are made at each stage and $p_{ij}$ represents the passage matrix, we assume that at each stage there is a change of state, a change that depends on the initial state, the final state, and the decision made. Assuming that the initial state of the system is known, the problem is choosing an optimal policy in the field of waste from collected electrical and electronic equipment.

The input values in this Markov chain are information taken from the National Agency for Environmental Protection regarding the amount of electrical and electronic equipment placed on the market and the amount of waste from electrical and electronic equipment collected.

The model designed to estimate the amount of electrical and electronic equipment placed on the market and the amount of waste from electrical and electronic equipment collected is based on the Markov chain.

The model is structured in two stages:

Stage 1: Establishing the annual reference value

This is done at the beginning of the calendar year and helps to set real targets on the amount of electrical and electronic equipment placed on the market and the level of waste collection from electrical and electronic equipment.

Stage 2: Estimating for the analyzed year:

During this phase, the Markov process will be used to estimate the amount of electrical and electronic equipment placed on the market and the amount of waste collected from these types of equipment.

Because Markov-type processes are processes without memory, the entire evolution of the system is rendered by the last observed moment. This is how they will define:

- System and component states;
- The logical structure of the system will be established;
- The probabilities of transition from one state to another are established;
- Solutions are obtained in time functions, representing the state probabilities of the system;

Because stage 1 will be achieved, it will be possible to make a clear forecast on the amount of electrical and electronic equipment placed on the market and the amount of waste from electrical and electronic equipment collected since the beginning of the year. Thus, for the amount of waste from electrical and electronic equipment collected, the recovery percentage of 65% will be applied 65% of the quantity of electrical and electronic equipment placed on the market (annual average over the last 3 years).

Because each country has its specificity, the integration of the Markov process into the developed calculation methodologies that meet the requirements of “Enforcement Regulation (EU)2017/699” involves the development of a more predictable system on which to develop and implement public policies in the field of environment [39].

Predictability is an essential element in the collection and recycling of waste from electrical and electronic equipment. Countries, such as Romania, need to develop systems through which they can reach a similar level of collection and recycling as performing countries due to their ability to collect and recycle.

The model proposed by this paper integrates perfectly with the European Directive and emphasizes the immediate history of each actor involved in the production, marketing, collection, and recycling of electrical and electronic equipment.

The integration of this model into the European reporting toolkit (e-tools) is based on the Weibull Distribution, which is one of the most used law in practice because it can model phenomena of different forms [43,50,51].

The integration of the estimated values through the proposed model in the European instrument is easy to achieve and can lead to an increase in the collection, recycling and implicitly will help to achieve the proposed targets according to the legislation in force. Thanks to this model, a clear prediction will be made regarding the quantity of electrical and electronic equipment placed on the market and the waste from the electrical and electronic equipment collected. It will also be known what are the expectations of each interested party in the production, marketing, and collection of this type of equipment.

To have a real basis in the process of estimating the quantities of electrical and electronic equipment and waste from electrical and electronic equipment collected in the period 2022-2032, we used official data from the National Environmental Protection Agency. According to the Report of the National Environmental Protection Agency, the amount of electrical and electronic equipment placed on the market in the period 2012-2018 for each category of electrical and electronic equipment and the total amount is shown in table 1 [52,53]:

**Table no. 1: The quantity of electrical and electronic equipment places on the market for each category and their annual total**

| Category | Quantities of EEE (tons) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
| “1. Large household appliances” | 74.755,61 | 81.810,67 | 84.995,17 | 103.475,36 | 129.548,53 | 140.581,085 | 146.794,551 |
| “2. Small household appliances ” | 14.641,71 | 13.655,46 | 10.466,12 | 14.667,61 | 16.224,62 | 18.467,346 | 22.675,785 |
| “3. IT and telecommunications equipment “ | 12.423,31 | 13.759,41 | 13.400,46 | 13469,45 | 13.231,54 | 15.230,911 | 16.031,34 |
| “4. Consumer equipment and photovoltaic panels” | 12.267,52 | 11.704,91 | 14.832,53 | 15.236,29 | 17.594,37 | 27.702,545 | 26.189,225 |
| “5. Lighting equipment ” | 6.052,09 | 6.363,55 | 5.350,9 | 6.010,49 | 7.042,15 | 9.084,300 | 13.666,494 |
| “6. Electrical and electronic tools (with the exception of large-scale stationary industrial tools) ” | 7.556,19 | 7.339,87 | 7.727,25 | 9.654,61 | 11.108,44 | 18.030,341 | 23.935,021 |
| “7. Toys, leisure and sports equipment ” | 812,9 | 654,42 | 999,47 | 1.616,51 | 2.150,54 | 3.489,874 | 4.718,887 |
| “8. Medical devices (with the exception of all implanted and infected products)” | 423,57 | 416,79 | 394,51 | 673,90 | 564,86 | 889,331 | 1.430,596 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| “9. Monitoring and control instruments” | 1.245,3 | 750,14 | 938,16 | 2.566,35 | 2.126,21 | 3.343,294 | 4.539,39 |
| “10. Automatic dispensers” | 369,85 | 348,97 | 482,54 | 808,83 | 1.093,56 | 1.225,335 | 1.169,184 |
| TOTAL | 130.548,1 | 136.804,2 | 139.587,1 | 168.179,40 | 200.684,82 | 238.044,36 | 261.150,47 |

Source: National Agency for Environmental Protection [52,53]

As mentioned above, starting with 2019, the 10 categories of electrical and electronic equipment have switched to 6 categories according to Directive 2012/19 /EU [3], transposed into the Romanian legislation by “O.U.G. nr. 5/2015” on waste from electrical and electronic equipment [4].

- Application of the developed instrument

To apply the model described above in the simulation process to establish the values of electrical and electronic equipment put on the market in the period 2022-2032, we used the following working hypotheses:

a. The reference values for the quantity of electrical and electronic equipment put on the market are those related to the period 2019-2021, as they are in “Annual report on the state of the environment in Romania, year 2022”, year, document produced by the National Agency for Environmental Protection [54].
b. The reference values for the amount of waste from electrical and electronic equipment are those related to the period 2019-2021, as they are in the “Annual report on the state of the environment in Romania, year 2022”, a document produced by the National Agency for Environmental Protection [54].
c. Estimates of the total quantity of electrical and electronic equipment put on the market for the period 2022-2032 shall be calculated as the average of the last three years. The exception is the years for which we already have this information 2019-2021.
d. Estimates of the total amount of waste from electrical and electronic equipment collected for the period 2022-2032 will be calculated as 65% of the average over the last three years of the total quantity of electrical and electronic equipment placed on the market. This complies with the requirement of the European Directive 2012/19. The exception is the years for which we already have this information 2019-2021.
e. The calculation of the estimated quantity of each category of electrical and electronic equipment put on the market in the period 2022-2032 is made using the Markov chain.
f. Calculation of the estimated quantity of each category of waste from electrical and electronic equipment collected in the period 2022-2032 is made using the Markov chain.
g. In these simulations will work with three decimal places because in the reports of the National Agency for Environmental Protection, the information is also passed with three decimal places.

To perform the simulations, Matlab software was used. Information that is normally found in matrix form has been centralized in tabular form for better visualization of results. Within the thesis, for the years 2022-2023 were made integral calculations, both for the quantity of electrical and electronic equipment placed on the market and for the quantity of waste from electrical and electronic equipment collected. Also for the two years mentioned above, both the tabular and the matrix form were used.

For the period 2024-2032, the detailed information was presented in Annex no. 1 for electrical and electronic equipment placed on the market and Annex no. 2, no, for the amount of waste from electrical and electronic equipment collected.

The application of the Markov model for the quantity of electrical and electronic equipment placed on the market to calculate the quantities in each category of equipment in 2022 is presented below. As we said before, the application of this tool is carried out during two stages:

Stage 1: Establishing the annual reference value

According to the National Agency for Environmental Protection, in the period 2019-2021, the six categories of electrical and electronic equipment put on the market are distributed as follows [54]:

**Table no. 2 Amount of EEE placed on the market during 2019-2021**

| Category | Quantities of EEE (tons) | | |
|---|---|---|---|
| | 2019 | 2020 | 2021 |
| “1. Temperature exchange equipment ” | 77.574,175 | 84.911,802 | 91.311,804 |
| “2. Screens, monitors, and equipment containing screens having a surface greater than 100 cm$^{P}$)” | 25.520,678 | 26.063,396 | 25.759,219 |
| “3. Lamps ” | 2.132,268 | 2.434,092 | 2.367,245 |
| “4. Large equipment (any external dimension more than 50 cm) ” | 117.611,907 | 122.863,772 | 158.693,063 |
| “5. Small equipment (no external dimension more than 50 cm) ” | 57.311,506 | 62.672,907 | 75.113,020 |
| “6. Small IT and telecommunication equipment (no external dimension more than 50 cm)” | 9.584,868 | 10.100,607 | 10.356,015 |
| TOTAL | 289.735,401 | 309.046,576 | 363.600,366 |

Source: National Environmental Protection Agency [54]

As you can see from table no. 1 next “large equipment”, “heat transfer equipment” and “small size equipment” have the highest share of the amount of electrical and electronic equipment put on the market.

The Markov chain method used is one of the most accessible and at the same time, precise methods and has the major advantage that it can be applied easily on a short data series, in the case under consideration the reference period is three years (2019-2021).

In order to calculate the 2022 information on the total amount of EEE and the amount broken down for each category of EEE placed on the market, we took into account the following:

- ➢ The total estimated quantity for 2022 is calculated as the average of the last 3 years: (289.735,401+309.046,576+363.600,366)/3= 320.794,114 tons.
- ➢ The related quantity for each category of EEE in 2022 depends on the most recent value in the system. In the analyzed case, the most recent values are those related to 2021.

Stage 2: Making the estimate for the year analyzed:

In the context of the above, the application of the Markov chain to predict the estimation of the quantities of each of the six categories of electrical and electronic equipment put on the market for 2022 is based on the previous evolution of the equipment weights in the quantity total of equipment. Taking into account the law of probabilities of passage, it shows the trend by which the quantities of each product group are demanded on the market.

Starting from the information found in table no. 1, we determined the structure of each group of electrical and electronic equipment in percentages.

**Table no. 3: Structure of each EEE group (%)**

| Categorie EEE | 2019 | 2020 | 2021 |
|---|---|---|---|
| “1. Temperature exchange equipment ” | 26,774% | 27,475% | 25,113% |
| “2. Screens, monitors, and equipment containing screens having a surface greater than 100 cm$^P$)” | 8,808% | 8,433% | 7,084% |
| “3. Lamps ” | 0,736% | 0,788% | 0,651% |
| “4. Large equipment (any external dimension more than 50 cm) ” | 40,593% | 39,756% | 43,645% |
| “5. Small equipment (no external dimension more than 50 cm) ” | 19,781% | 20,279% | 20,658% |
| “6. Small IT and telecommunication equipment (no external dimension more than 50 cm)” | 3,308% | 3,268% | 2,848% |
| TOTAL | 100.00% | 100.00% | 100.00% |

Because the Markov chain is based on the model, the quantity of electrical and electronic equipment placed on the market shown in Table 2 is further transposed as a matrix. Thus, the matrix associated to table no. 3 is as follows:

$$A = \begin{pmatrix} 77.574{,}175 & 84.911{,}802 & 91.311{,}804 \\ 25.520{,}678 & 26.063{,}396 & 25.759{,}219 \\ 2.132.268 & 2.434{,}092 & 2.367{,}245 \\ 117.611{,}907 & 122.863{,}772 & 158.693{,}063 \\ 57.311{,}506 & 62.672{,}907 & 75.113{,}020 \\ 9.584{,}868 & 10.100{,}607 & 10.356{,}015 \end{pmatrix}$$

To make estimates it is necessary to calculate the passing or transition matrices from one group to another (for example, from 2019 to 2020, from 2020 to 2021). In the analyzed situation we have “n-1” (2 matrices) crossing or transition matrices.

To reach these matrices, the changes that occur with the transition from 2019 to 2020 are established. This information is presented in Table no. 4

**Table no 4: Determination of the changes that occur with the changeover from year 2019 To 2020 (%)**

| Years | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 2019 | 26,774% | 8,808% | 0,736% | 40,593% | 19,781% | 3,308% |
| 2020 | 27,475% | 8,433% | 0,788% | 39,756% | 20,279% | 3,268% |
| Differences | 0,701% | -0,375% | 0,052% | -0,837% | 0,499% | -0,040% |

From the previous calculations, it can be seen that the absolute values of the positive values gathered have the same absolute value as the negative values gathered (-1,252=1,252).

**Table no. 5: Transition matrix from 2019 to 2020 (%)**

| Category | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | 26,774 | 0,000 | 0,000 | 0,000 | 0,000 | 0,000 |
| 2 | 0,210 | 8,434 | 0,016 | 0,000 | 0,149 | 0,000 |
| 3 | 0,000 | 0,000 | 0,736 | 0,000 | 0,000 | 0,000 |
| 4 | 0,469 | 0,000 | 0,035 | 39,756 | 0,334 | 0,000 |
| 5 | 0,000 | 0,000 | 0,000 | 0,000 | 19,781 | 0,000 |
| 6 | 0,022 | 0,000 | 0,002 | 0,000 | 0,016 | 3,268 |

The transposition of the information from table no. 5 in matrix form has the following form:

$$B = \begin{pmatrix} 26,774 & 0,000 & 0,000 & 0,000 & 0,000 & 0,000 \\ 0,210 & 8,434 & 0,016 & 0,000 & 0,149 & 0,000 \\ 0,000 & 0,000 & 0,736 & 0,000 & 0,000 & 0,000 \\ 0,469 & 0,000 & 0,035 & 39,756 & 0,334 & 0,000 \\ 0,000 & 0,000 & 0,000 & 0,000 & 19,781 & 0,000 \\ 0,022 & 0,000 & 0,002 & 0,000 & 0,016 & 3,268 \end{pmatrix}$$

To achieve all the transitions in the analyzed period, the changes that occur with the transition from 2020 to 2021 will be further established.

**Table no. 6: Establishing the changes that occur with the transition from the year 2020 to 2021 (%)**

| Years | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 2020 | 27.475% | 8.433% | 0.788% | 39.756% | 20.279% | 3.268% |
| 2021 | 25.113% | 7.084% | 0.651% | 43.645% | 20.658% | 2.848% |
| Differences | -2.362% | -1.349% | -0.137% | 3.889% | 0.379% | -0.420% |

From the previous calculations, it can be seen that the absolute values of the positive values gathered have the same absolute value as the negative values gathered (-4,268=4,268).

**Table no. 7: Transition matrix from 2020 to 2021 (%)**

| Category | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| 1 | 25,113 | 0,000 | 0,000 | 2,153 | 0,210 | 0,000 |
| 2 | 0,000 | 7,085 | 0,000 | 1,229 | 0,120 | 0,000 |
| 3 | 0,000 | 0,000 | 0,651 | 0,124 | 0,012 | 0,000 |
| 4 | 0,000 | 0,000 | 0,000 | 39,756 | 0 | 0,000 |
| 5 | 0,000 | 0,000 | 0,000 | 0,000 | 20,279 | 0,000 |
| 6 | 0,000 | 0,000 | 0,000 | 0,383 | 0,037 | 2,848 |

Transposition of previous information into matrix form:

$$C = \begin{pmatrix} 25,113 & 0,000 & 0,000 & 2,153 & 0,210 & 0,000 \\ 0,000 & 7,085 & 0,000 & 1,229 & 0,120 & 0,000 \\ 0,000 & 0,000 & 0,651 & 0,124 & 0,012 & 0,000 \\ 0,000 & 0,000 & 0,000 & 39,756 & 0,000 & 0,000 \\ 0,000 & 0,000 & 0,000 & 0,000 & 20,279 & 0,000 \\ 0,000 & 0,000 & 0,000 & 0,383 & 0,037 & 2,848 \end{pmatrix}$$

Summing up the terms of the two pass matrices determines the matrix of the total passes.

**Table no. 8: Transition total matrix (2019-2021)**

| Category | 1 | 2 | 3 | 4 | 5 | 6 | |
|---|---|---|---|---|---|---|---|
| 1 | 51,887 | 0,000 | 0,000 | 2,153 | 0,210 | 0,000 | 54,250 |
| 2 | 0,210 | 15,518 | 0,016 | 1,229 | 0,269 | 0,000 | 17,242 |
| 3 | 0,000 | 0,000 | 1,387 | 0,124 | 0,012 | 0,000 | 1,524 |
| 4 | 0,469 | 0,000 | 0,035 | 79,512 | 0,334 | 0,000 | 80,349 |
| 5 | 0,000 | 0,000 | 0,000 | 0,000 | 40,060 | 0,000 | 40,060 |
| 6 | 0,022 | 0,000 | 0,002 | 0,383 | 0,053 | 6,117 | 6,577 |

Transposition of previous information into matrix form:

$$D = \begin{pmatrix} 51,887 & 0,000 & 0,000 & 2,153 & 0,210 & 0,000 \\ 0,210 & 15,518 & 0,016 & 1,229 & 0,269 & 0,000 \\ 0,000 & 0,000 & 1,387 & 0,124 & 0,012 & 0,000 \\ 0,469 & 0,000 & 0,035 & 79,512 & 0,334 & 0,000 \\ 0,000 & 0,000 & 0,000 & 0,000 & 40,060 & 0,000 \\ 0,022 & 0,000 & 0,002 & 0,383 & 0,053 & 6,117 \end{pmatrix} = \begin{pmatrix} 54,250 \\ 17,242 \\ 1,524 \\ 80,349 \\ 40,060 \\ 6,577 \end{pmatrix}$$

Since we have the total pass matrix, one can calculate the pass probability matrix. Thus, each term of the new matrix is calculated by dividing the elements related to the matrix of total crossings by the total values on each line of the total crossings matrix. The sum of these probabilities thus obtained must be equal to 1. This information is summarised in Table no. 9.

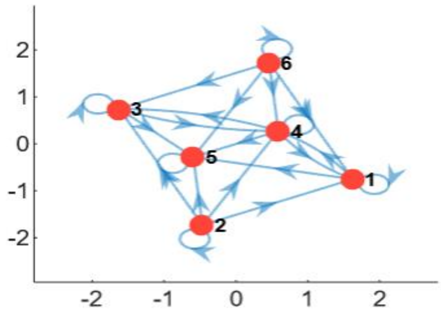
**Table no.9: The matrix of the probabilities of transition (2019-2021)**

| | | | | | | |
|---|---|---|---|---|---|---|
| 0,956 | 0,000 | 0,000 | 0,040 | 0,004 | 0,000 | 1 |
| 0,012 | 0,900 | 0,001 | 0,071 | 0,016 | 0,000 | 1 |
| 0,000 | 0,000 | 0, 910 | 0,082 | 0,008 | 0,000 | 1 |
| 0,006 | 0,000 | 0,0004 | 0,990 | 0,004 | 0,000 | 1 |
| 0,000 | 0,000 | 0,000 | 0,000 | 1,000 | 0,000 | 1 |
| 0,004 | 0,000 | 0,0003 | 0,058 | 0,008 | 0,930 | 1 |

Transposition of previous information into matrix form:

$$E = \begin{pmatrix} 0,956 & 0,000 & 0,000 & 0,040 & 0,004 & 0,000 \\ 0,012 & 0,900 & 0,001 & 0,071 & 0,016 & 0,000 \\ 0,000 & 0,000 & 0,910 & 0,082 & 0,008 & 0,000 \\ 0,006 & 0,000 & 0,0004 & 0,990 & 0,004 & 0,000 \\ 0,000 & 0,000 & 0,000 & 0,000 & 1,000 & 0,000 \\ 0,004 & 0,000 & 0,0003 & 0,058 & 0,008 & 0,930 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}$$

**Figure no.1 Graph of the probabilities of transition matrix (2019-2021)**




Markov graph is useful in the simulation because it can visualize and understand the qualitative evolution of the categories of electrical and electronic equipment put on the market. The pass probability matrix graph provides an intuitive insight into how a system can evolve from one state to another and the probability with which it evolves.

Through the graphical representation of the transitions between the categories of electrical and electronic equipment, trends and potential changes are identified in the need for electrical and electronic equipment to be put on the market.

The nodes represent each category of electrical and electronic equipment, the arches indicate the transitions between them. In the graph presented can be seen the change of requirements from the point of view of the consumer market. For example, category 5 represents “5 - Small-sized equipment (no external size greater than 50 cm)” and is highlighted by an increase at the expense of the other categories.

To see if the above-mentioned are supported, we must analyze the evolution of the six categories of electrical and electronic equipment in 2022.

As I mentioned in Stage 1, the total quantity of equipment put on the market in 2022 is calculated as the average of the last three years. Thus this estimated total quantity is: (289.735,401+309.046,576+363.600,366)/3= 320.794,114 tons. Having the total quantity and the matrix of the passing probabilities, we can calculate the quantities related to each category of electrical and electronic equipment placed on the market.

To achieve this forecast for 2022, we will multiply the total probability matrix by the column matrix related to the year 2021.

$$\begin{pmatrix} 0{,}956 & 0{,}012 & 0{,}000 & 0{,}006 & 0{,}000 & 0{,}004 \\ 0{,}000 & 0{,}900 & 0{,}000 & 0{,}000 & 0{,}000 & 0{,}000 \\ 0{,}000 & 0{,}001 & 0{,}910 & 0{,}0004 & 0{,}000 & 0{,}0003 \\ 0{,}040 & 0{,}071 & 0{,}082 & 0{,}990 & 0{,}000 & 0{,}058 \\ 0{,}004 & 0{,}016 & 0{,}008 & 0{,}004 & 1{,}000 & 0{,}008 \\ 0{,}000 & 0{,}000 & 0{,}000 & 0{,}000 & 0{,}000 & 0{,}930 \end{pmatrix} \mathrm{X} \begin{pmatrix} 25{,}113 \\ 7.084 \\ 0{,}651 \\ 43{,}645 \\ 20{,}658 \\ 2{,}848 \end{pmatrix}$$

The values obtained from this multiplication are listed in Table 9. Because the total quantity of electrical and electronic equipment placed on the market in 2022 is also known (320.794,114 tons), with the help of the values obtained as a result of the multiplication of previous matrices, we can calculate the quantity of each category of electrical and electronic equipment placed on the market.

**Table no. 10: Quantities in each category of EEE put on the market in 2022**

| | | |
|---|---|---|
| Category 1 | 24,370% | 78.178,809 |
| Category 2 | 6,376% | 20.454,474 |
| Category 3 | 0,619% | 1.984,112 |
| Category 4 | 44,911% | 144.071,203 |
| Category 5 | 21,075% | 67.607,680 |
| Category 6 | 2,649% | 8.497,836 |
| Total | 100% | 320.794,114 |

The application of the Markov model for the amount of waste collected from electrical and electronic equipment for 2022 goes through the same steps. The input elements in the simulation process are also data from the National Agency for Environmental Protection, in the period 2019-2021, the quantity of WEEE collected in the six categories is distributed as follows [54]:

**Table no. 11: Amount of WEEE collected during 2019-2021**

| Categoriy | Quantities of WEEE (tons) | | |
|---|---|---|---|
| | 2019 | 2020 | 2021 |
| "1. Temperature exchange equipment " | 19.764,140 | 20.173,210 | 18.967,810 |
| "2. Screens, monitors, and equipment containing screens having a surface greater than 100 cm$^P$)" | 10.283,450 | 9.873,065 | 13.467,713 |
| "3. Lamps " | 399,240 | 430,295 | 152,198 |
| "4. Large equipment (any external dimension more than 50 cm) " | 42.292,400 | 43.814,166 | 44.457,082 |
| "5. Small equipment (no external dimension more than 50 cm) " | 6.292,840 | 8.803,657 | 8.427,881 |

| | | | |
|---|---|---|---|
| "6. Small IT and telecommunication equipment (no external dimension more than 50 cm)" | 8.590,960 | 5.404,468 | 4.037,488 |
| TOTAL | 87.623,020 | 88.498,861 | 89.510,172 |

Source: National Environmental Protection Agency [54]

To determine the quantity of each category of electrical and electronic waste collected were obtained taking into account the following entry elements:

- The estimated total quantity of electrical and electronic equipment put on the market for 2022 is calculated as the average of the last 3 years: (289.735,401+309.046,576+363.600,366)/3= 320.794,114 tons.
- Complying with the requirements of Directive 2012/19/EU, the amount of waste collected in electrical and electronic equipment is 65% of the average over the last three years. Thus, this amount is 65% x 320.794,114 =208.516,174 tons.
- The corresponding amount for each category of waste from electrical and electronic equipment in 2022 depends on the most recent value in the system. In the analyzed case, the most recent values are those related to 2021.

Applying the above-described steps, the quantity of each category of waste from electrical and electronic equipment collected for 2022 is obtained.

**Table no. 12: Quantities of each category of WEEE collected in 2022**

| | | |
|---|---|---|
| Category 1 | 20,546% | 42.842,567 |
| Category 2 | 16,149% | 33.672,860 |
| Category 3 | 0,123% | 256,683 |
| Category 4 | 50,127% | 104.523.111 |
| Category 5 | 10,047% | 20.948,786 |
| Category 6 | 3,008% | 6.272,167 |
| Total | 100% | 208.516,174 |

- Analysis of the results obtained by applying the Markov model

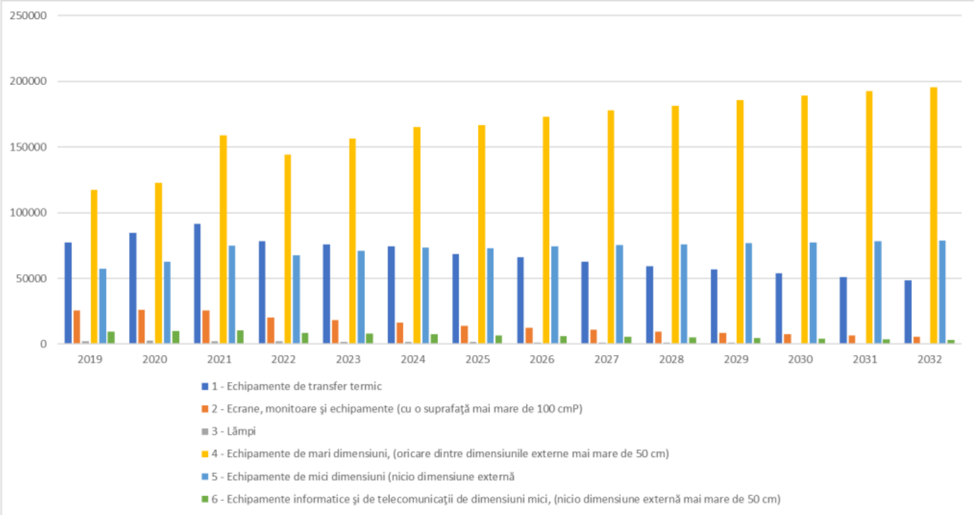
According to Directive 2012/19/EU, for the period 2019-2021 the collection target established is 65% of the quantity placed on the market by electrical and electronic equipment (annual average of 3 years) or 85% of the quantity of waste from electrical and electronic equipment [3].

Tot în temeiul aceleiași Directive 2012/19/UE, România a decis, prin derogare de la paragraful 1, articolul 7, să amâne adoptarea ratei de colectare dar cel târziu la 14 august 2021 [3]. Cu toate acestea, România nu este singura țară care a făcut apel la derogarea de mai sus. Din cauza lipsei infrastructurii necesare și a nivelului scăzut de consum de echipamente electrice și electronice, alte țări europene au decis să amâne adoptarea ratei de colectare. Aceste țări sunt: Bulgaria, Republica Cehă, Letonia, Lituania, Ungaria, Malta, Polonia, Slovenia și Slovacia [3].

The proposed model is a tool that helps every entity involved in this process. Thus, it can be used both by those who produce and market EEE and by those who collect or recycle WEEE. The model may also be used by the regulatory entity.

With the previous application of this model, one can observe the evolution of the quantity of electrical and electronic equipment placed on the market. This development can be seen in figure no. 2.

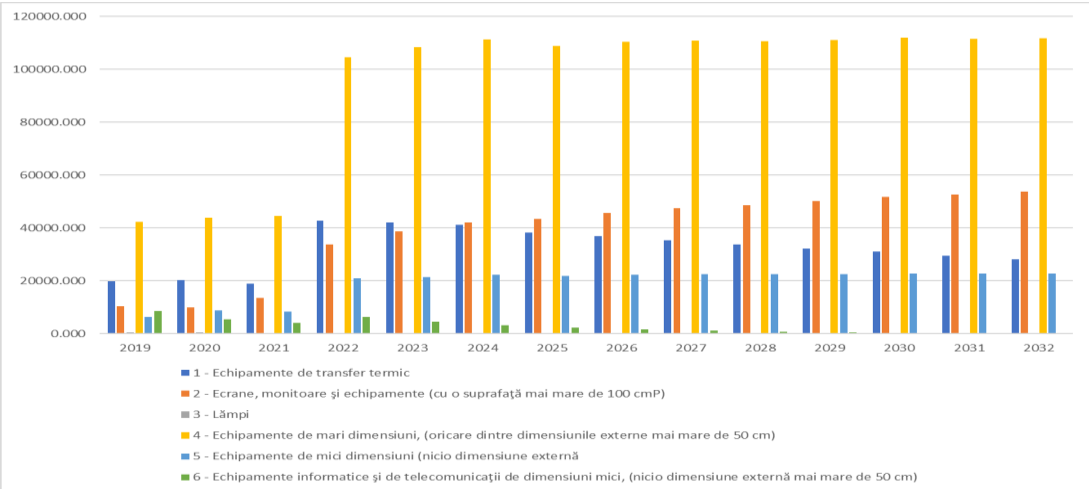
**Figure no. 2 Evolution of the quantity of electrical and electronic equipment placed on the market in 2019-2032**




From the previous graph, it can be seen that the amount of electrical and electronic equipment placed on the market in each category is realistically constant. This supports the need to implement a sustainable model that can be easily integrated into the European reporting model.

In terms of the amount of waste collected in electrical and electronic equipment, the application of the previous model led to the results shown in figure no. 3.

**Figure no. 3 Evolution of waste from electrical and electronic equipment collected in 2019-2032**




In the previous figure we can see the major gap between the degree of collection of waste from electrical and electronic equipment in 2019-2021 and the degree of collection of such waste in the period for which the simulation was 2022-2032. This gap also derives from the lack of an approach based on a forecast of the management of electrical and electronic equipment and, implicitly, of the waste generated from them.

The use of a model based on the Markov chain predicts the advantage that the future state depends only on the present state, not on the entire system history, which makes it easy to apply and integrate into the European instrument.

The mathematical model used is an essential tool in optimizing this complex process. By obtaining the estimated values, one can see which categories of waste have the highest share and in this respect can develop programs and policies that can help the process.

The proposed mathematical model is a tool for improving the efficiency and sustainability of waste collection systems.

The European e-tools instrument is based on the Weibull distribution. The integration of a model related to the Markov chain in such an instrument provides a strong approach to shaping a dynamic system with random components such as the evolution of the quantity of electrical equipment and electronics placed on the market and, implicitly, waste from electrical and electronic equipment collected.

The integration of the two models can be beneficial because:

- the Markov model describes the discrete states of the system and the transition probabilities between them, the Weibull distribution represents the time allotted for the transition from one state to another.
- when the time allocated for a state is completed, the system transitions to a new state, thus respecting the transition probabilities of the Markov model. The process is repeated until all the states are covered.
- the Weibull distribution offers flexibility in shaping the service life of components, allowing different forms of distribution.

The integration of Weibull distribution with the proposed Markov model provides a safe and clear approach to modeling dynamic systems with random components such as electrical and electronic equipment. It also has the advantage of being able to provide time estimation of the analyzed processes.

## Economic value of the developed instrument

Chapter VII. “The economic value of the developed“ tool shows the economic impact of this process, which is a significant one due to the many benefits it has. The economic and social benefits are the most obvious. Thus, among them can be listed:

a. Economic benefits
    - Creating new jobs in various fields of activity related to the process of waste collection, sorting, repair, and recycling;
    - Saving resources through the collection and recycling process allows the recovery and reuse of valuable materials such as iron, nickel, and gold. This reduces the need for new extraction of such materials, which can have a significant impact on the environment.
    - Reducing waste management costs because collection and recycling reduces the cost of waste storage.
b. Socials benefits:
    - Improving health: recycling waste from electrical and electronic equipment reduces environmental pollution and risks to human health.
    - Protecting the environment: increasing recycling of waste from electrical and electronic equipment contributes to the conservation of natural resources, the reduction of pollution and the fight against climate change.
c. Recycling waste from electrical and electronic equipment contributes to the emergence and development of new industries based on the circular economy, such as:
    - Repair industry: Repair and refurbish waste from electrical and electronic equipment for reuse.
    - Recycled materials production industry: Innovative materials are produced from recycled materials from waste from electrical and electronic equipment.

- ➢ Industry of dismantling: Disassembling waste from electrical and electronic equipment to recover valuable components and materials.

d. In addition to traditional industries, new industries are also developing with increasing recycling. Thus, companies can be developed that:
    - ➢ To produce furniture from recycled material.
    - ➢ Recondition and repair electronic equipment.
    - ➢ Waste removal services to recover valuable components and materials.

It can be seen that at all stages of the collection and recycling process new jobs can be created. This process brings major benefits to the economy by:

- ➢ New jobs generate revenue and contribute to the growth of the economy.
- ➢ Provides employment opportunities for people with diverse qualifications.
- ➢ Provides training programs to develop the skills needed in this sector.
- ➢ Provides employment opportunities for disadvantaged or marginalized people.

The economic field by which electrical and electronic equipment is developed is identified as one of the priority sectors with great opportunities for the possibilities of the circular economy.

There is significant potential for generating revenue from waste from electrical and electronic equipment, but there is no official system for the reuse of products, and therefore, no expected revenue is created.

## Sustainable prospects for the collection and recycling of waste electrical and electronic equipment

Chapter VIII. “Sustainable prospects for the collection and recycling of waste electrical and electronic equipment ” presents the sustainable directions of the developed model:

a. Improving infrastructure:
    - ➢ Developing an adequate infrastructure for the collection of waste from electrical and electronic equipment, with easily accessible collection points in urban and rural areas.
    - ➢ Investments in modern and efficient recycling facilities, equipped with advanced technologies to maximize material recovery.

b. Stimulating producer responsibility:
    - ➢ Implementation of the "expanded producer responsibility" principle obliges producers to finance the collection and recycling of waste from electrical and electronic equipment.
    - ➢ Introduction of warranty-return systems to facilitate the collection of waste from electrical and electronic equipment from users.

c. Increasing awareness:
    - ➢ Information and public education campaigns on the importance of collecting and recycling waste from electrical and electronic equipment.
    - ➢ Promoting responsible consumer practices, such as the purchase of energy-efficient and sustainable products.

d. Development of new technologies :
    - ➢ Innovation in the recycling of waste from electrical and electronic equipment to improve the efficiency and cost-effectiveness of processes.
    - ➢ Development of new materials from recycled materials from waste from electrical and electronic equipment.

e. International cooperation:

- Enhancing cooperation between countries to facilitate the exchange of information and best practices in the collection and recycling of waste from electrical and electronic equipment.
- Harmonization of legislation on waste from electrical and electronic equipment at the international level to facilitate cross-border waste management.

The implementation of the previously presented sustainable perspectives has benefits that cannot be challenged. These benefits are:

- Protecting the environment: reducing environmental pollution and preserving natural resources by reducing the storage and incineration of waste from electrical and electronic equipment.
- Boosting the economy: creating new jobs and business opportunities in the waste recycling industry from electrical and electronic equipment.
- Improving public health: reducing exposure to hazardous substances present in waste from electrical and electronic equipment.

As we mentioned earlier, in the recycling process of waste from electrical and electronic equipment, the following valuable materials are obtained:

- Precious metals: gold, silver, platinum, palladium. These materials can be used in jewelry, electronics, and other industrial products.
- Common metals: copper, aluminum, and iron that can be used in construction, automobile, and other industrial products.
- Plastics: various types of plastic that can be used to produce new plastic products, such as containers, pipes, and garden furniture.
- Glass: glass of different colors and types that can be used to produce new bottles, building materials, and other products.
- Electronic components: integrated circuits, capacitors, and resistors, can be repaired and reused or used to produce new electronic components.

## Measures to increase the collection and recycling of waste electrical and electronic equipment

Chapter IX. “Measures on increasing the collection and recycling of waste electrical and electronic equipment” present the real necessary measures that can stimulate this industry. These measures can be listed:

a. Extended producer responsibility:
    - The obligation for manufacturers to collect and recycle a specific amount of waste from electrical and electronic equipment is commensurate with the volume of electrical and electronic equipment placed on the market.
    - Introduction of guarantee-return systems, with financing from manufacturers.
    - Supporting manufacturers designing electrical and electronic equipment that is easy to disassemble and recycle.
b. Informing and raising public awareness :
    - Information campaigns on the importance of collecting and recycling waste from electrical and electronic equipment.
    - Educating the public about the dangers of improper storage of waste from electrical and electronic equipment.
    - Promoting selective waste collection programs for electrical and electronic equipment.

c. Improving the collection infrastructure:

- Extension of the network of waste collection points from electrical and electronic equipment.
- Facilitating public access to collection points.
- Introduction of easy collection systems, such as home collection.

d. Financial incentives :
   - Providing financial incentives for the collection and recycling of waste from electrical and electronic equipment.
   - The introduction of charges for the storage of waste from electrical and electronic equipment in landfills.
   - Granting discounts on the purchase of new electrical and electronic equipment for those who teach the old ones.

e. Cooperation between authorities, producers and non-governmental organizations:
   - Developing national strategies for the management of waste from electrical and electronic equipment.
   - Implementation of joint programs for the collection and recycling of waste from electrical and electronic equipment.
   - Organizing information and education campaigns for the public.

f. Developing new technologies for recycling waste from electrical and electronic equipment.
g. Supporting research and innovation on waste from electrical and electronic equipment.
h. Promoting the circular economy in the field of electrical and electrical equipment.

## General conclusions

Waste from electrical and electronic equipment can be considered a resource of valuable metals such as copper, aluminum, and gold. Where such resources are not recovered, raw materials must be extracted and processed to produce new products, resulting in significant loss of resources and environmental damage. Their non-collection can also have a major impact on the environment and human health.

While some countries are lagging in increasing the collection and recycling of waste from electrical and electronic equipment, different countries have proposed and implemented strategies to meet these challenges. Unfortunately, Romania is one of the countries where none of the collection targets has been reached.

With this paper, we have developed a tool to estimate the amount of electrical and electronic equipment placed on the market and the collection of related waste. This tool has been applied for ten years to see how feasible it is. Thus, the results obtained are adequate and reflect the image of the Romanian market in terms of the amount of electrical and electronic equipment placed on the market and of the waste collected from them.

## Original contributions

The thesis belongs to the field of environmental protection with an emphasis on increasing the level of waste collection from electrical and electronic equipment. The proposed model has an interdisciplinary approach based on the Markov process.

Starting with European and National regulations, the developed model offers a new and predictable perspective on the industry that aims to collect and recycle waste from electrical and electronic equipment.

The use of a model based on the Markov chain predicts the advantage that the future state depends only on the present state, not on the entire system history, which makes it easy to apply and integrate into the European instrument.

The European e-tools instrument is based on the Weibull distribution. The integration of a model related to the Markov chain in such an instrument provides a strong approach to shaping a dynamic system with random components such as the evolution of the quantity of electrical equipment and electronic put on the market and implicitly of the collected waste.

The mathematical model used is an essential tool in optimizing this complex process. By obtaining the estimated values, one can see which categories of waste have the highest share and in this respect can develop programs and policies that can help the process.

The proposed model is also a tool to improve the efficiency and sustainability of waste collection systems.

## Prospects for further development

During the development of the doctoral thesis and after obtaining the final results, the following future research directions were outlined:

- Development and implementation of complex software that based on the simulations can realize a waste management plan;
- Extension of research on the environmental impact of new technologies;
- To develop research on the recovery processes of the elements that can be used from waste from electrical and electronic equipment;

Note: This summary includes in a concise form the content of the doctoral thesis chapters. The name of the chapters is the one corresponding to the thesis. The numbering of tables and figures does not correspond to that in the sentence. The bibliographic references presented in the abstract are part of those used in the paper, for this reason, the bibliography will be fully included in this summary.

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