Deconvolution: an analysis of theses and dissertations and their relevance to the nuclear area

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Abstract. Convolution and deconvolution (inverse convolution operation) are mathematical methods used for processing signals and images, and can be applied in different areas of knowledge, such as Astronomy, Geology and Medicine. In order to demonstrate its relevance in research in Brazil, this paper aimed to carry out a bibliographic review, through the Bank of Theses and Dissertations (BTD) of the Coordination of Higher Education Personnel (CAPES), of works carried out on the theme, and analyze, through the scientific knowledge management, the works carried out in nuclear area. It is understood that, although few works were found in the nuclear area, the use of the deconvolution process is evolving, considering its importance for spectrometry analyses, mainly for Metrology, an activity that is extremely relevant for the country.

1. Introduction

In mathematics, it can be said that both convolution and deconvolution (which is the inverse operation of deconvolution) are used for signal and image processing. Particularly in the area of functional analysis and signal processing, convolution is a linear operator that, from two given functions, results in a third that measures the sum of the product of these functions over the region implied by their superposition as a function of displacement existing among themselves [1]. The concept of convolution is linked to the superposition integral in Fourier optics, to the Duhamel integral in vibration theory, to Borel's Theorem in the study of linear time-invariant systems, to the concept of moving average, to correlation and autocorrelation functions. In statistics and signal processing, and to several concepts used in image analysis, such as digitization, smoothing, blurring and chromatic aberration [1].

The notation for the convolution of “f” and “g” is “f” x “g”. It is defined as the integral of the product of one of the functions by a shifted and inverted copy of the other; the resulting function “h” depends on the displacement value. If “x” is the independent variable and u the displacement, the formula can be written as [1]:

$$(f * g)(x) = h(x) = \int_{-\infty}^{\infty} f(u) \cdot g(x-u)\, du \quad (1a)$$

Note that h(x) depends on f(x) and g(x) but, to calculate h(x1), it is not enough to know f(x1) and g(x1); it is necessary to know the values of f(x) and g(x) over the entire interval $-\infty < x < \infty$. If the time variable is inserted, we have [1]:

$$(f * g)(t) = h(t) = \int_{-\infty}^{\infty} f(\tau) \cdot g(t - \tau)\, d\tau \quad (1b)$$

Deconvolution is the inverse operation of convolution. In this case, it is possible to recover the original signal after a filter (convolution) using a deconvolution method with a certain degree of precision, which can be applied in several areas of knowledge, such as astronomy (radioastronomy), biology (miscroscopy), physics (physics nuclear) and geology (seismology), for example [2]. The foundations for deconvolution and time series analysis were largely laid down by Norbert Wiener of the Massachusetts Institute of Technology (MIT) in his 1949 book “Extrapolation, Interpolation, and Smoothingo of Stationary Time Series” [3].

The book was based on work that Wiener had done during World War II but had been classified at the time. Some of the first attempts to apply these theories were in the areas of weather forecasting and economics [3; 4]. While working on enemy missile prediction, Norbert Wiener eventually developed a statistical procedure to separate radar signals from unwanted noise. Initially called “smoothing”, “Wiener prediction filtering” and “decomposition”, it is now called “deconvolution”. Deconvolution acts on the time axis, seeking to reduce the influence of the source pulse on the received signal so that substrate information is acquired more faithfully, improving the temporal resolution of the data [3; 4].

It is possible to divide deconvolution into two large groups: Probabilistic and Deterministic. Deterministic methods are applied when there is knowledge about the shape of the signal sent by a source, while Probabilistic methods consist in the use of statistical theories to obtain it [3].

Mathematically, the goal of deconvolution is to find the solution f of a convolution equation of the form: f x g = h. Normally, h is some recorded signal and f is some signal that we want to recover, but has been convolved with a filter or distortion function g, before recording it [4; 5]. The function g can represent the transfer function of an instrument or a driving force that has been applied to a physical system. If g is known, or at least the form of g, then deterministic deconvolution can be performed. However, if g is not known in advance, it is necessary to estimate [4; 5].

Most often, this is done using statistical estimation methods. In Physical editions, the situation is usually closer to (f x g + ε) = h [5]. In this case, ε is the noise that entered our recorded signal. If a noisy signal or image is considered noiseless, the statistical estimate of g will be incorrect. In turn, the estimate of f will also be incorrect. The lower the signal-to-noise ratio, the worse the estimate of the devolved signal [5].

This is the reason why reverse signal filtering is usually not a good solution. However, if there is at least some knowledge of the type of noise in the data (e.g. white noise), the estimate of f can be improved through techniques such as Wiener deconvolution. Deconvolution is usually performed by calculating the Fourier transform of the recorded signal h and the distortion function (generally known as the transfer function) g. Deconvolution is then performed in the frequency domain (in the absence of noise) using F = H/G, where F, G and H are the Fourier transforms of , g and h, respectively [5]. Finally, the inverse Fourier transform of the function F is used to find the estimated deconvolved signal f. [5].

2. Materials and Methods

In this sense, in view of the range of applications, the relevance of the deconvolution process, the lack of a review on the application of this methodology in Brazil, this paper aims to evaluate, through the Bank of Theses and Dissertations (BTD) of the Coordination of Support for Higher Education

Personnel (CAPES) the production on the subject, as the BTD is understood as an indicator of bibliographic production [6].

A qualitative-quantitative research [7] was carried out, identifying and classifying the works (qualitative research) and carrying out a quantitative analysis by area of knowledge, using the keyword “deconvolution”. This is because it is intended to verify, in the end, the relevance of the theme specifically in the nuclear area.

Papers whose keyword “deconvolution” was found either in the title, or in the abstract or in the keywords were selected. At the end, a specific search was made for the nuclear area, in the case of Higher Education Institutions (HEIs) linked to the National Nuclear Energy Commission (CNEN) that have *Stricto Sensu* graduate programs, namely [8]:

• Center for the Development of Nuclear Technology (CDTN) – Postgraduate Program in Science and Technology of Radiation, Minerals and Materials;

• Northeast Regional Nuclear Science Center (CRCN) – Postgraduate Program in Energy and Nuclear Technologies;

• Institute of Nuclear Engineering (IEN) – Postgraduate Program in Nuclear Science and Technology;

• Institute of Energy and Nuclear Research (IPEN) – Postgraduate Program in Nuclear Technology; and

Institute of Radiation Protection and Dosimetry (IRD) – Postgraduate Program in Radiation Protection and Dosimetry.

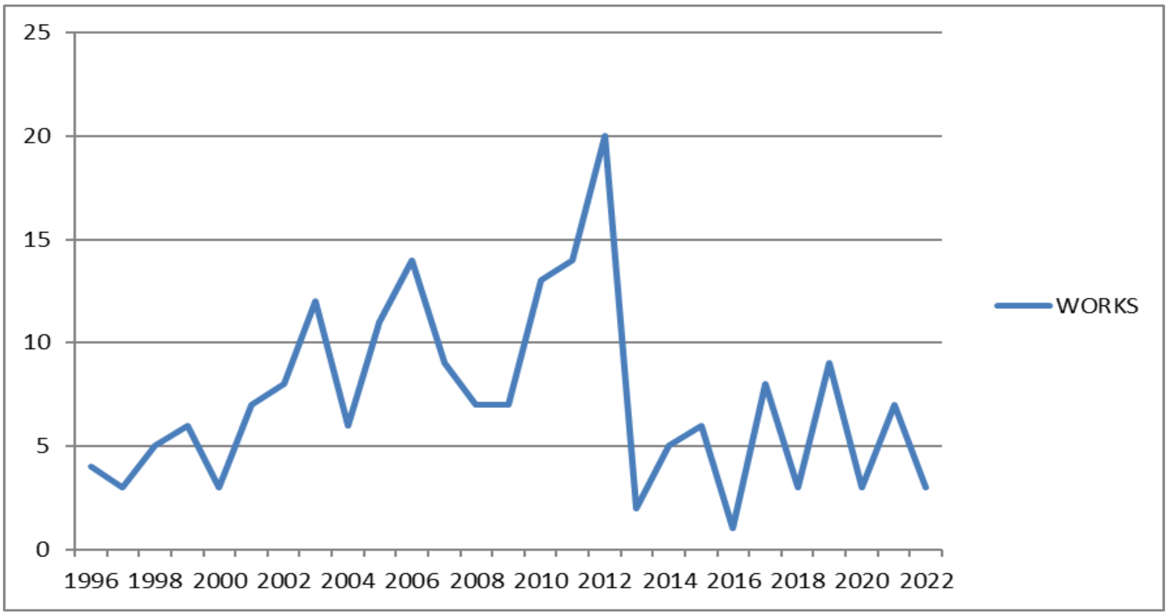
In this sense, this work was developed in order to carry out a bibliographic review aimed at scientific knowledge management on the application of deconvolution in studies in the nuclear area. This is because it can be said that the understanding of scientific knowledge itself, by a teaching and research institution, ends up promoting advances in its activities, helping in the technological innovation of its respective area of activity [9].

3. Results and Discussion

3.1. General result by Concentration and Evaluation Areas

A total of 216 works were found when using the keyword “deconvolution”, of which 135 theses (Doctorade or Ph.D.) and 81 dissertations (Master), between the years 1996 and 2022 (Figure 1).

Figure 1. Evolution of work over the years



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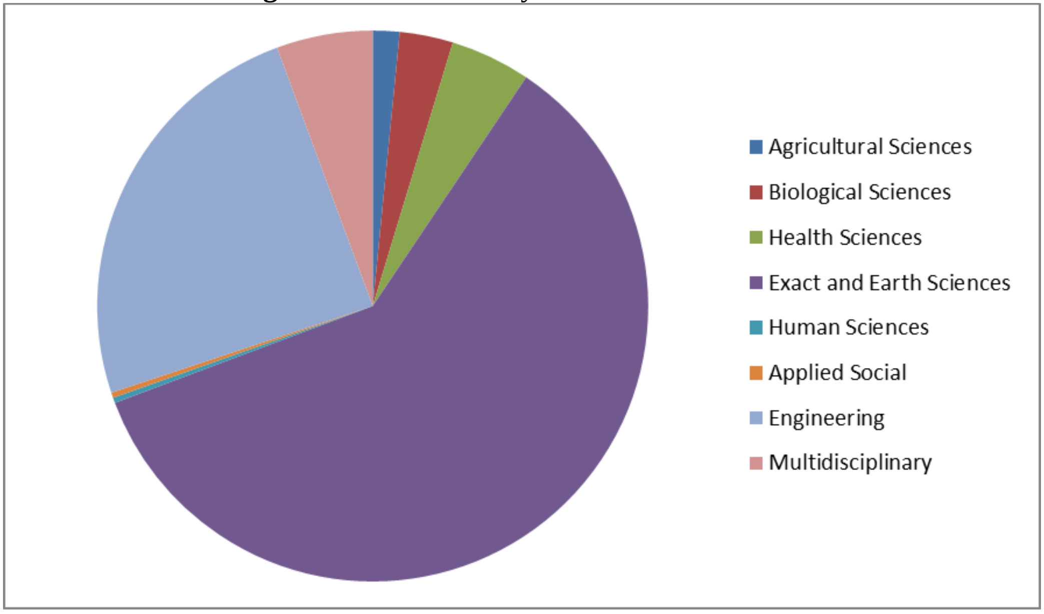
It is possible to verify the presence of works on deconvolution during all years, having its peak between the years 2010 and 2012. In total, works were found in 8 Knowledge Areas [7][1], being distributed as follows (Figure 2):

- Agricultural Sciences (5)
- Biological Sciences (10)
- Health Sciences (15)
- Exact and Earth Sciences (191)
- Human Sciences (1)
- Applied Social Sciences (1)
- Engineering (78)
- Multidisciplinary (18).

[1] According to CAPES, there are 9 areas of knowledge: Exact and Earth Sciences; Biological Sciences; Engineer-ing; Health Sciences; Agricultural Sciences; Social and Applied Sciences; Human Sciences; Linguistics, Letters and Arts; and Multidisciplinary. In addition, there are a total of 49 Evaluation Areas

Figure 2. Distribution by Concentration Area



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Here, there is a greater concentration in the areas of Exact and Earth Sciences, followed by Engineering, which is natural, considering the mathematical applications. However, it is possible to find works in all areas of knowledge (except Linguistics), showing the applicability of the method.

Finally, works were found in 40 Assessment Areas (out of a total of 49), namely:

- Astronomy / physics (34)
- Biotechnology (1)
- Computer Science (7)
- Food Science (4)
- Agricultural Sciences (1)
- Environmental Sciences (1)
- Biological Sciences I (5)
- Biological Sciences II (4)
- Biological Sciences III (1)
- Economy (1)
- Engineering I (6)
- Engineering II (31)
- Engineering III (22)
- Engineering IV (20)
- Pharmacy (5)
- Geosciences (104)
- Geography (1)
- Interdisciplinary (6)
- Mathematics / probability and statistics (3)
- Materials (7)
- Medicine I (5)
- Medicine II (4)
- Medicine III (1)
- Multidisciplinary (3)
- Chemistry (43)

3.2. Results for Nuclear Area

Specifically for works that involved the nuclear area, the works described in Table 1 were found.

Table 1. Deconvolution for the nuclear area

TITLE	AUTHOR	M /D	YEAR	PROGRAM	HIE
Mean cross-section measurements in the U-235 fission spectrum, for some threshold reactions [10]	MAIDANA, N. L.	M	1993	Nuclear Technology	University of São Paulo/ Institute for Energy and Nuclear Research
Photoproduction of Neutrons in Th-232 and U-238 with Gamma Radiation of Thermal Neutron Capture in the Energy Range between 5.61 to 10.83 meV [11]	LELIS, G. O.	D	1998	Nuclear Technology	University of São Paulo/ Institute for Energy and Nuclear Research
Applications of quadrupole nuclear resonance in two dimensions [12]	RODRIGUES, H. J. C.	D	1998	Physical	University of São Paulo
X and Gamma Emission Probabilities Determined by Spectrometry in Complex Regions [13]	DELGADO, J. U.	D	2000	Nuclear Engineering	Federal University of Rio de Janeiro
Study of Neural Networks for Application in Neutron Spectrometry and Dosimetry [14]	BRAGA, C. C.	D	2001	Nuclear Technology	University of São Paulo/ Institute for Energy and Nuclear Research
Inverse problems in experimental physics: the photonuclear cross section and electron-positron annihilation radiation [15]	TAKIYA, C.	D	2003	Physical	University of São Paulo
Effects of gamma irradiation on b-lactoglobulin: structural changes and aggregation [16]	URREJOLA, L. DEL C. DE LA H.	D	2006	Food and Nutrition	Campinas State University
Measurements of ^{9}Be, ^{13}C and ^{17}O Photoneutron Cross Sections with Thermal Neutron Capture Gamma radiation [17]	SEMMLER, R.	D	2006	Nuclear Technology	University of São Paulo/ Institute for Energy and Nuclear Research
Unfolding neutron spectra using the Monte Carlo method and neural networks [18]	JUNIOR, R. M. DE L.	D	2009	Nuclear Engineering	Federal University of Rio de Janeiro
Study and evaluation of bubble detectors for neutron field measurements [19]	DANTAS, J. E. R.	M	2010	Nuclear Engineering	Federal University of Rio de Janeiro
Deconvolution of neutron spectra obtained with the EB-TLD system using genetic algorithm [20]	SANTOS, J. A. DE L.	D	2011	Nuclear Energy Technologies	Federal University of Pernambuco
Synthesis, microstructural and electrical characterization of ceramic compounds based on solid solutions of strontium titanate, calcium titanate and iron oxide [21]	CARMO, J. R. DO	D	2011	Nuclear Technology	University of São Paulo/ Institute for Energy and Nuclear Research

Applications of the Warren-Averbach method of diffraction profile analysis [22]	ICHIKAWA, R. U.	M	2013	Nuclear Technology	University of São Paulo/ Institute for Energy and Nuclear Research
Use of multivariate normal functions in the study of the fragmentation of sulfur-containing molecules ionized by electrons and photons [23]	VARAS, L. J. R.	D	2016	Chemistry	Federal University of Rio de Janeiro
Studies of Thermoluminescence (TL), Paramagnetic Resonance (EPR) and Optical Absorption (AO) properties for characterization of the mineral Monticelite [24]	QUINA, A. DE J. A. DE	M	2016	Nuclear Technology	University of São Paulo/ Institute for Energy and Nuclear Research
Primary standardization of complex decay radionuclides by pico-sum coincidence method and photon spectrometry with GeHP detector [25]	SILVA, R. L. DA	D	2017	Radiation Protection and Dosimetry	Institute of Radiation Protection and Dosimety
Absolute standardization of Ra-223 and calibration of LNMRI reference systems [26]	SIMOES, R. F. P.	D	2018	Radiation Protection and Dosimetry	Institute of Radiation Protection and Dosimety
In vivo dosimetry using EPID [27]	SILVEIRA, T. B. DA	D	2018	Radiation Protection and Dosimetry	Institute of Radiation Protection and Dosimety
Artificial bee colony-based algorithm for deconvolution of neutron spectra obtained with Bonner spheres [28]	SILVA, E; R. DA	D	2019	Radiation Protection and Dosimetry	Institute of Radiation Protection and Dosimety
Personal dose equivalent Hp (10) in diagnostic imaging using OSL detectors based on Brazilian fluorite [29]	PAGOTTO, I.	M	2021	Biomedical engineering	Federal Technological University of Paraná
Theoretical study of the spectroscopic and structural properties of LiF, EuF_3, AF_2 (A = Ca, Sr and Ba) doped with Eu^{+3} [30]	MESQUITA, B. R. DE	D	2021	Physical	Federal University of Sergipe
Study of Bonner spectrometer responses with spheres of different polymeric materials [31]	MENDES, L. M. M.	M	2021	Science and Technology of Radiation, Minerals and Materials	Nuclear Technology Development Center/Federal University of Minas Gerais
Application of spectral deconvolution algorithms to estimate probabilities of Ra-223 photon emission in complex regions [32]	RAMOS, M. DOS S.	M	2021	Radiation Protection and Dosimetry	Institute of Radiation Protection and Dosimety

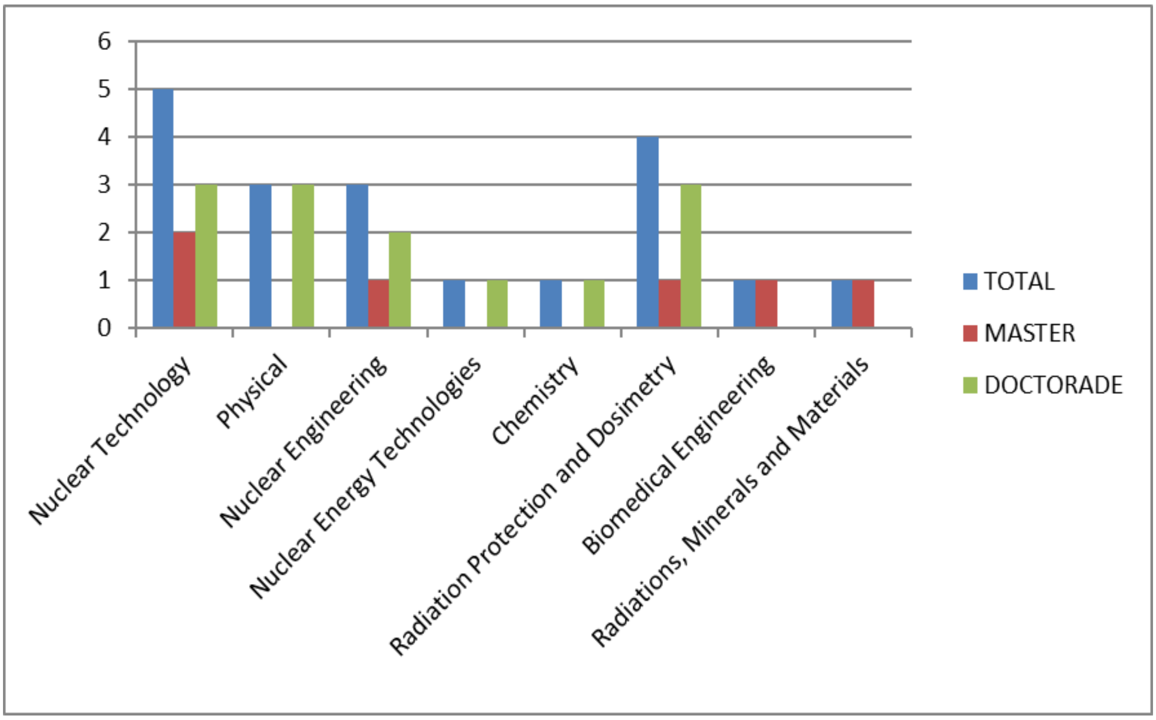
Source: The author. M – Master; D – Doctorade.

According to Table 1, 23 works were found in the nuclear area, which corresponds to 10.65% of the total found on deconvolution in the BTD. The works were defended between the years 1993 and

2022, 7 of which were Masters and 16 Ph.Ds., in 9 Graduate Programs from 8 different HIEs, namely (Figure 3):

- Nuclear Technology – 7 works (3M and 4D from the University of São Paulo/Energy and Nuclear Research Institute);
- Physics – 3 (2D from the University of São Paulo and 1D from the Federal University of Sergipe);
- Nuclear Engineering – 3 (1M and 2D from the Federal University of Rio de Janeiro);
- Food and Nutrition – 1 (1D from the State University of Campinas);
- Nuclear Energy Technologies – 1 (1D from the Federal University of Pernambuco);
- Chemistry – 1 (1D from the Federal University of Rio de Janeiro);
- Radiation Protection and Dosimetry – 5 (1M and 4D from the Institute of Radioprotection and Dosimetry);
- Biomedical Engineering – 1 (1M from the Federal Technological University of Paraná); and
- Science and Technology of Radiation, Minerals and Materials – 1 (1M from the Nuclear Technology Development Center of the Federal University of Minas Gerais).

Figure 3. Distribution by Programs in the Nuclear Area

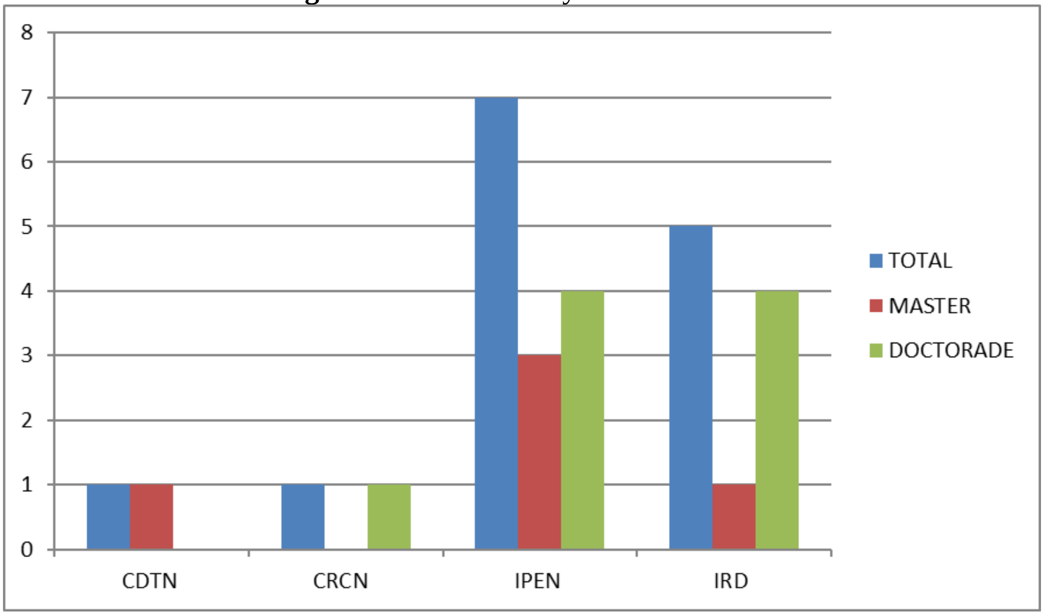


Source: The author

Thus, the works involved different applications in the nuclear area, as in the study of Gamma Radiation, of Photonuclear Reactions, of Neutron Spectrometry, for Analysis of X-ray Diffraction Profiles, for the Probability of Photon Emission, of Mass Spectroscopy by flight time, for Metrology, Primary Standardization, Dosimetry, Radiological Protection and Radiotherapy; in the study of sources such as ^{133}Ba, ^{223}Ra and $Eu^{+3;}$ and mathematical methods such as Genetic Algorithms, Fourier Analysis, Warren-Averbach Method, Artificial Intelligence and Computational Modeling. Specifically with regard to HIEs linked to CNEN, 14 studies were found, which corresponds to 6.50% of the total on deconvolution and 60.87% in the nuclear area. Thus, the distribution of works is as follows (Figure 4):

• CDTN - 1 work [31], 1 dissertation;
• CRCN – 1 work [20], 1 thesis;
• IPEN – 7 works [10; 11; 14; 17; 21; 22; 24], being 3 dissertations and 4 theses; and
• IRD – 5 works [25; 26; 27; 28; 32], 1 dissertation and 4 theses.

Figure 4. Distribution by CNEN HIEs



Source: The author

4. Conclusion

Despite being a field of application and study in graduate studies (the first work was only carried out in 1996), the range of applications of deconvolution can be observed, given the presence of works in 8 of the 9 Evaluation Areas and 40 of the 49 Areas of Concentration.

Specifically regarding the use of deconvolution in the nuclear area, a total of 10.65% was found, which demonstrates the attention and application of the method in the various graduate programs. With regard to HIEs linked to CNEN, this value rises to 60.87%, demonstrating the wide application of the method.

In this sense, it is worth mentioning that one of the main objectives of this work was to carry out a scientific knowledge management of deconvolution, since it was not possible to find more data in the national bibliography. Thus, it is understood that this analysis can help in future works on the subject.

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