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ECOLOGICAL MODERNISATION – AN ECO-INNOVATIVE SOLUTION FOR THE PROCESS OF STRATEGIC PLANNING AND DESIGN OF WASTEWATER COLLECTION INFRASTRUCTURE

EXECUTIVE SUMMARY OF THE PHD THESIS

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2017

1. Introduction and motivation

Wastewater collection represents a major challenge in rural areas and in small towns. Nowadays the focus on a sustainable and resilient wastewater infrastructure is reduced considering the context of global economic crisis, climate change, and potential natural disasters.

The thesis evaluates two alternative systems of wastewater collection (conventional with lift stations versus vacuum system) from the perspectives of attributes of Ecological Modernisation Theory (EMT) and Resilience.

This scientific approach examines the capacity of Ecological Modernisation Theory (Hajer and Wagenaar, 1995; Mol, 1995; Christoff, 1996; Hajer, 1996; Cohen, 1997a; Jänicke, 2010*),* used as a paradigm for decision making process in the field of wastewater collection , to ensure sustainability, competitivity and the commercial success of eco-innovative technologies versus classical technologies for wastewater collection.

The thesis points out, in terms of ecological modernisation, on the capacity of eco-innovative technologies to contribute to the greening of wastewater collection systems.

Since the field of environmental engineering concerns aspects related to the technological and economic components of development of certain products or processes and their impact on the environment, in this specific scientific approach, only some themes of the Ecological Modernisation Theory are identified as being relevant.

In this regard, the study explores the techno- corporatist version of ecological modernisation, called also the engineering or weak version, that focus on the role of science and technology in providing development win-win solutions to the environment and economy.

The techno-corporatist variant of the EMT (Hajer, 1995; Cristoff, 1996) focuses on the implementation of advanced, innovative technologies that has to take into account, since design stage, the efficient use of resources and the mitigation of environmental impact during operation period. Thus, the super-technologisation is seen as a measure to overcome the ecological crisis through monetary investments that lead to the internalization of environmental externalities in the cost of the new product.

Moreover, the thesis investigates another key element of the EMT that has in view the availability of the information concerning the innovation and the adoption of eco-innovative technologies. Therefore, on the offer chain can emerge problems related with the availability, rapid transfer and acceptation of eco-innovative technologies.

The study explores the degree of ecological modernisation of the alternative sewer systems, through the evaluation of the capacity of classical versus eco-innovative technologies to overcome the environmental crises, with a focus on the investigation of radical innovation (vacuum sewer system) and of their adoption at global level. Another line of analysis focuses on the economic and environmental valuation of these technologies both at design level and operational conditions.

The analysis of institutional reform and of social movements does not make the subject of this scientific approach due to general limitations generated by high degree of bureaucracy in the relation with actors involved in the process of strategic planning, of a non-participatory process in the set up of the county strategies on water and wastewater issues, based exclusively on contracting experts on strategic planning.

Meanwhile, the debates around the policies in the water and wastewater infrastructure focus on the need to promote the resilience, the tendency more pronounced in the advanced economies (Walker and al., 2004; Walker and Salt, 2006; IPCC, 2007b; WHO, 2009).

Considering the potential natural and anthropic risks the wastewater infrastructure is facing, the study explores the performance and the degree of ecological modernisation of wastewater collection systems also from a point of view of resilience.

The infrastructure resilience, defined as the ability of a system to reduce the magnitude and the duration of events with destructive effects through the ability to anticipate, absorb, adapt and fast recover following these events (Holling, 1973; Walker and al., 2004; Resilience Alliance, 2007; Wu and Wu, 2013), is seen in this scientific framework as a possible component of ecological modernisation, aspect that was not approached before in the literature. The need of analysis of the economic, technological and environmental risks that concern the sewer infrastructure is generated by the practical aspects of design and urban planning. In this regard, it is highly important that the local authorities apply the diagnosis of the wastewater collection infrastructure since the design stage.

2. Objectives of the thesis

The thesis integrates two main lines of analysis. The first line approaches the available eco-innovative technologies in wastewater collection versus classical ones and concludes on their economic, social and environmental impact in terms of ecological modernisation. The second line of analysis makes a comparative analysis of two alternative wastewater systems in terms of resilience attributes and represents a window of opportunity for the introduction of resilience as an instrument to measure the degree ecological modernisation. Therefore, indirectly, there are evaluated the challenges the local actors involved in the decision-making process, but also the opportunities that derive from the analysis of the alternatives, that can lead to the forecasting of their impact and solutions to improve the functioning of wastewater collection systems since design stage.

The final objective is to explore the relation between the ecological modernisation and resilience by evaluating the use of economic instruments and of eco-innovation in providing and implementing competitive technologies for wastewater collection.

The study suggests the introduction of resilience as a new pillar of ecological modernisation, together with the economical, ecological and institutional reform and the role of social movements. The approach proposed in this scientific research by adopting the concept of resilience of infrastructure, integrates, besides the two main analysed pillars of engineering EMT (economic and technological reform), another two aspects: capacity of fast

recovery following certain natural or anthropic pressures and the economic, social and environmental reliability of two alternative wastewater collection systems.

The aim and the objectives of the thesis:

In the light of those exposed before, the thesis examines the applicability of engineering variant of EMT and of the concept of resilience of infrastructure in the process of decision making within the wastewater management, in order to ensure the sustainability and the competitivity of wastewater collection technologies.

The general objective is to explore the degree of ecological modernisation of wastewater collection systems by evaluating the capacity of classical versus eco-innovative technologies in the field of wastewater collection to overcome the environmental crises with accent on:

- Investigation of radical innovations and their adoption at global level;
- Economic evaluation of classical versus eco-innovative technologies;
- Evaluation of environmental performance from the perspective of environmental externalities;
- Evaluation of resilience of the two wastewater collection systems;

The research objective is to identify the best environmental practices and innovations in the field of wastewater collection; to rank Romania in the hierarchy of the states that have adopted eco-innovative technologies for wastewater collection and to establish the driving forces that facilitate or impede the diffusion of eco-innovative sewer systems - engines for ecological modernization; to establish if the cost-benefit analysis, quantification of externalities of alternative wastewater systems and the resilience can be used as instrument to evaluate their ecological modernisation degree; and to formulate structural models that allow for the local authorities and the wastewater operators in wastewater management to contribute to the sustainability of water sector.

The specific objectives analyzed within this scientific approach are the following ones:

- to investigate the acceptance and implementation level of eco-innovative technologies for wastewater collection on a comparative comparatively basis, concentrating on the states that implemented vacuum sewer systems, including Romania;
- to compare two alternative wastewater collecting systems (classical versus vacuum sewer system) and to highlight the competitive advantages of each technology from a point of view of costs, benefits, and environmental externalities;
- to evaluate the achieved technological level and the modernisation opportunities of the chosen alternative wastewater systems, concomitantly with the analysis of analysis of the environmental externalities of wastewater collection systems;
- to select the wastewater system with the highest level of resilience;
- to reflect on those models of strategies and technologies for wastewater collection that can accelerate the reorientation of the infrastructure planning and design process that focus on the greening of wastewater collection system;

A first objective of the thesis was to investigate the technological level achieved by Romania in what concerns the introduction of eco-innovative wastewater collection technologies, in comparative basis with other states in the world, and to determine the tendencies and factors that stimulate or impede the diffusion of eco-innovation (Duncan, 1996; Johnstone, 2005; Gonzalez-Moreno and al., 2013; Gonzalez-Moreno and al., 2014).

The thesis tests the hypothesis that eco-innovative technologies have the capacity to overcome the ecological crisis of wastewater collection systems and their social, economic and environmental impact. Therefore, the thesis has the secondary objective to study the way in which the cost-benefit analysis *(*Rashid and Hayes, 2011) can be used as measurement instrument for ecological modernisation of the two alternative wastewater collection systems.

The study answers to a series of global challenges concerning the production of toxic and greenhouse gases, objective that was little approached in the literature in what concerns the generation of sewer gases at the level of sewer systems (Czepiel and al., 1993; Denman and al., 2007; Foley and al., 2009; Foley and al., 2010; Daelman and al., 2012, 2013; Lane and Lant, 2012).

Another objective of the study concerns the comparative analysis of vulnerabilities of alternative projects of wastewater collection systems exposed to sundry natural (natural disasters as earthquakes, landslides etc.) or anthropic disruptions (economic, technological, environmental) from the perspective of resilience (Resilience Alliance, 2007; Saaty, 1996a; Saaty 1996b, 2006, 2008; Saaty and Vargas, 2006, 2013a).

3. Research methodology

For the interpretation of ecological modernisation of wastewater collection systems three aspects were analyzed: technological reform, economic reform and the analysis of resilience of two alternative wastewater collection systems: conventional gravitational wastewater system with lift stations versus vacuum sewer system.

Considering the interdisciplinary character of the thesis, the methods used are specific to the environmental engineering, environmental sociology and to economic analysis.

The methods include:

3.1. The evaluation of eco-innovation adoption using as instruments logical-mathematical methods for *statistical data processing* (software SPSS) and geo statistics (GIS);

3.2. *Environmental management techniques*, respectively the technology of infrared sensors and chemical sensors for the determination of sewer gasses (gas analyzer), as well as mathematical modeling for the determination of emission factors for the main a analyzed sewer gasses (methane, hydrogen sulfide, carbon dioxide and carbon monoxide);

3.3. *Comparative cost-benefit analyses* to select the optimum alternative of wastewater collection system from economic and environmental point of view (own application on Excel based on literature and Cost- benefit analysis guides);

3.4. *Multi-criteria analysis* (analytical network process) for the determination of the resilience of two alternative technologies of wastewater collection by using the software SUPERDECISIONS, available at www.superdecisions.com)

4. Summary of scientific findings resulted from the analysis of the technological, economic and resilience reform of alternative wastewater collection systems

a. eco-innovation distribution

A prime objective of the thesis was to investigate the technological level attained by Romania in what concerns the introduction of eco-innovative wastewater systems, in a comparative basis with other states in the world and to determine the trends and factors that stimulate or impede the eco-innovation diffusion (Duncan, 1996; Johnstone, 2005; Gonzalez-Moreno and colab., 2013; Gonzalez-Moreno and colab., 2014).

This section evaluated the adoption of eco-innovation providing a different perspective on the forces that stimulate or impede the adoption of vacuum sewer system. The case study concludes that the structure of the market, the socio-economic conditions, the geographic proximity and the level of GDP measures the degree of acceptance of rejection of eco-innovation in what concerns providing the public goods.

This section presents the analytical model of the data analysis and the arguments behind the hypotheses that were tested in this work. The structure of the hypotheses was determined by three factors that were scrutinized and found to influence the adoption of innovation: period of adoption, general country economic performance and neighborhood conditions.

The research aim was to determine the main factors that facilitate or prevent the diffusion of eco-innovation in the world on a comparative basis. The research postulated three hypotheses:

Hypothesis I. There is a direct relationship between the stage of adoption of eco-innovation and the number of projects. The number of projects decreases along the stages of adoption due to saturation of the market in affluent countries, while emerging countries lag in the speed of adoption, but have the advantage of 'leapfroggers', reaching the most advanced technologies. This descendent trend in public investments field it is correlated also with the high life-span of the system, only some components being replaced periodically (vacuum valves).

Hypothesis II. The Gross Domestic Product (GDP) level influences the level of adoption of eco-innovation. There is an increase of adoption of eco-innovation proportional to the GDP level. The lead market and affluent countries experience the highest adoption rate, while countries with a small GDP situate at the periphery in what the adoption of innovation.

Hypothesis III. The neighborhood conditions determine the acceleration of eco-innovation adoption. The hypothesis tries to quantify the importance of spatial spillover effects on the evolution of eco-innovation adoption. The states neighboring the lead market have a higher

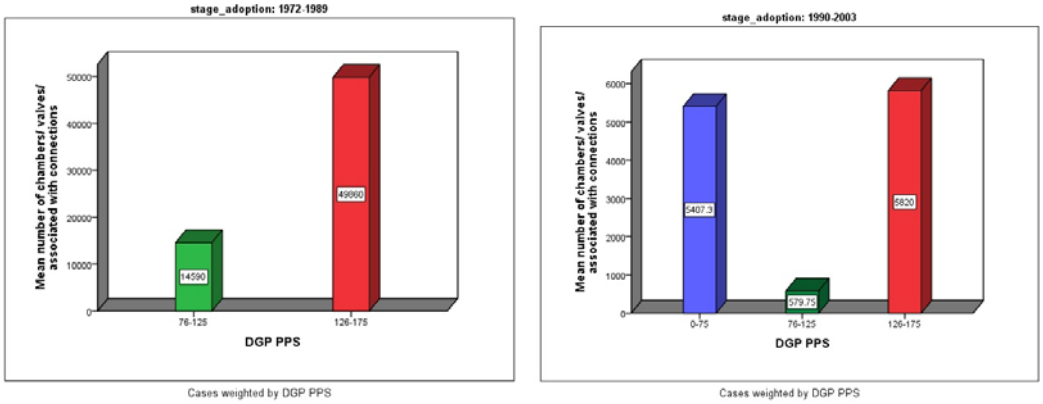
adoption rate due to the facile communication process between the source and the target and the operational aspects of the eco-innovation already in place. Neighboring countries may influence each other's technology uptake choices. We take into account that geography plays a major role in the distribution of economic activity, such that neighboring economies are more likely to converge than are distant ones.

Hypothesis IV. The geographical conditions influence the uptake of the eco-innovation; states with a higher percent of flat land have a higher uptake of vacuum sewer system.

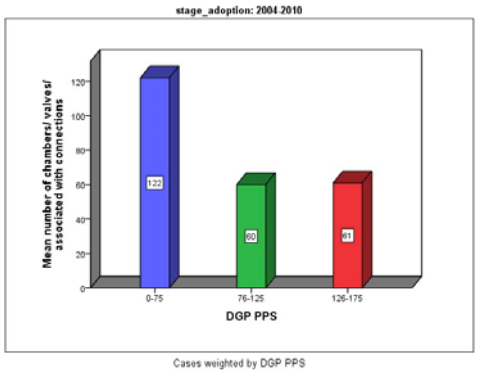
The vacuum system is suitable to be implemented on flat land; consequently, the measure of innovation is analyzed based on the percentage of flat land in participating countries correlated with the total number of collecting chambers**.**

The extent of greening of the sewer system was scrutinized on a comparative basis, having as inputs 39 states that have implemented vacuum sewer systems. The data made available by the two companies refer to projects implemented for the period of 1973–2008. To determine the level of diffusion of eco-innovation, a cross-country comparison of vacuum system projects was performed.

The cases of 39 countries were analyzed according to the following variables: stage of adoption, GDP, type of technology (Roediger or AIRVAC), year of technology adoption, period of execution, number of vacuum sewer implemented projects and collecting chambers: Australia (1); Austria (2), Bahamas (3) Bahrain (4), Botswana (5), Brazil (6), Brunei (7), Canada (8), China (9), Croatia (10), Czech Republic (11), France (12), Germany (13), Greece (14), Hungary (15), Iran (16), Ireland (17), Italy (18), Japan (19), Korea (20), Lithuania (21), Maldives (22), Malaysia (23), Morocco (24), Mexico (25), Namibia (26), the Netherlands (27), Oman (28), Poland (29), Portugal (30), Romania (31), Slovakia (32), Slovenia (33), Spain (34), Thailand (35), United Arab Emirates (36), United Kingdom (37), United States of America (38) and West Indies (39).



a) b)



c)

Figure 2. Relationship between the GDP-PPS, stage of adoption and number of connections (collecting chambers) corresponding to: a) – first (1972–1989); b) – second (1990–2003); c)– third (2004–2010) stage of adoption

Figure 2 shows the relationship between the GDP-PPS, the stage of adoption and number of connections.

The Figure 2, presents the relationship between the GDP PPS and number of connections (collecting chambers) corresponding to the three selected stages of eco-innovation adoption: a) – first (1972–1989); b) – second (1990–2003); c) – third (2004–2010) stage of adoption.

The figure 2.a) elicits that in the first stage of adoption of vacuum sewer system (1972–1989), the states with a higher GDP PPS have a higher trend of eco-innovation adoption than states with medium GDP PPS that had access to the vacuum system technology, trend measured by the number of connecting chambers.

The figure 2.b) corresponding to the second stage of adoption of vacuum sewer system (1990–2003), shows that the states with highest GDP PPS have the highest uptake of eco-innovative technology, followed by the states included in the category small GDP PPS, the states with medium GDP PPS being placed at periphery.

In what concerns the third stage of adoption (2004–2010) of the vacuum sewer system (Figure 2.c) it can be observed that the states with the smallest GDP-PPS highlight the highest level of eco-innovation adoption, followed by the countries with highest and medium level of GDP PPS.

The assessment of the relationship between the geographic proximity and the level of adoption of the eco-innovation in what concerns the two main providers of vacuum sewer system was relevant with regard to the distribution of projects and the number of vacuum chambers (Figure 3). The relationship is provided only for the European states that make the subject of the research. The results of the geostatistical analysis showed (Figure 3) that countries bordering Germany, the lead European market in supplying vacuum sewer technology, had a higher number of connections than did the other states placed at the periphery regarding the distance from the lead market, without direct relation with the level GDP PPS.

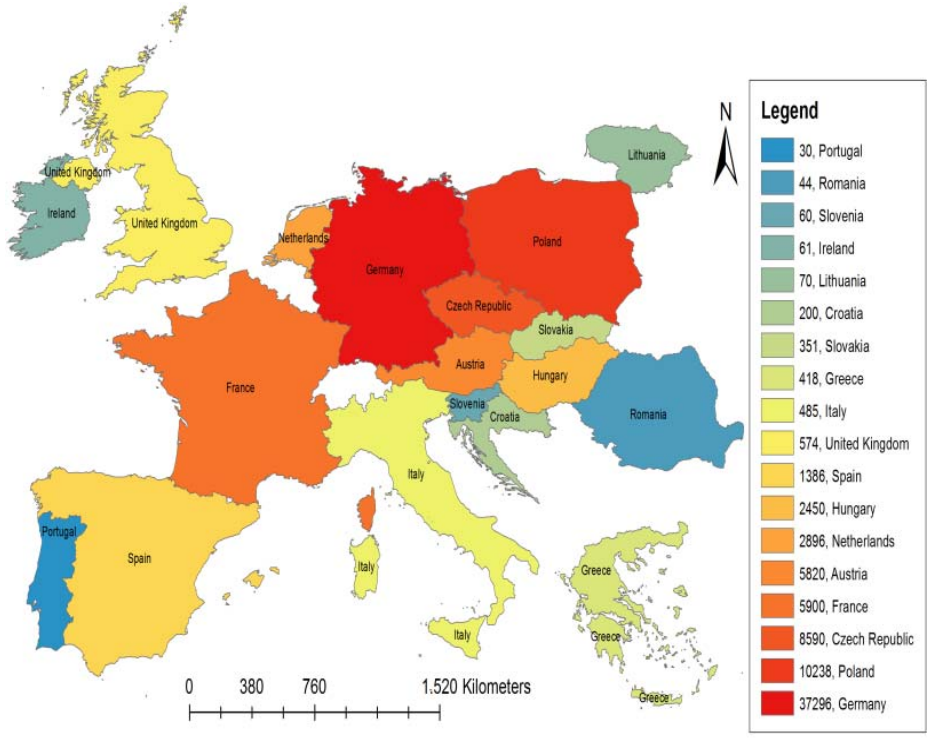


Figure 3. Distribution of vacuum sewer systems in Europe in relation to the lead market and number of collecting chambers realized by GIS application

The data concerning the uptake of sewer system in Europe were analysed from the perspective of beneficiary population of the states that make the subject of the case study. The main objective of establishing the correlation between the number of collecting chambers and population was to determine if the uptake of eco-innovation is an indicator to the political response to the social and environmental problems, related to the percentage of population that disposes of vacuum sewer system. Even though Germany is the one of the biggest producer of vacuum sewer system in Europe, as can be observed in the Figure 4, it ranks only on the fourth place (0,638%), being outranked by Austria, (3,192%) and Czech Republic (1,449%). States as Poland and Hungary occupy the next places in this rank. Romania ranks on the last place in this hierarchy with a percent of 0,004% from the population that might represent the target group of vacuum sewer projects.

Figure 4 depicts the relation between the population living on low-lands area and number of collecting chambers for the states that make the objective of the case study

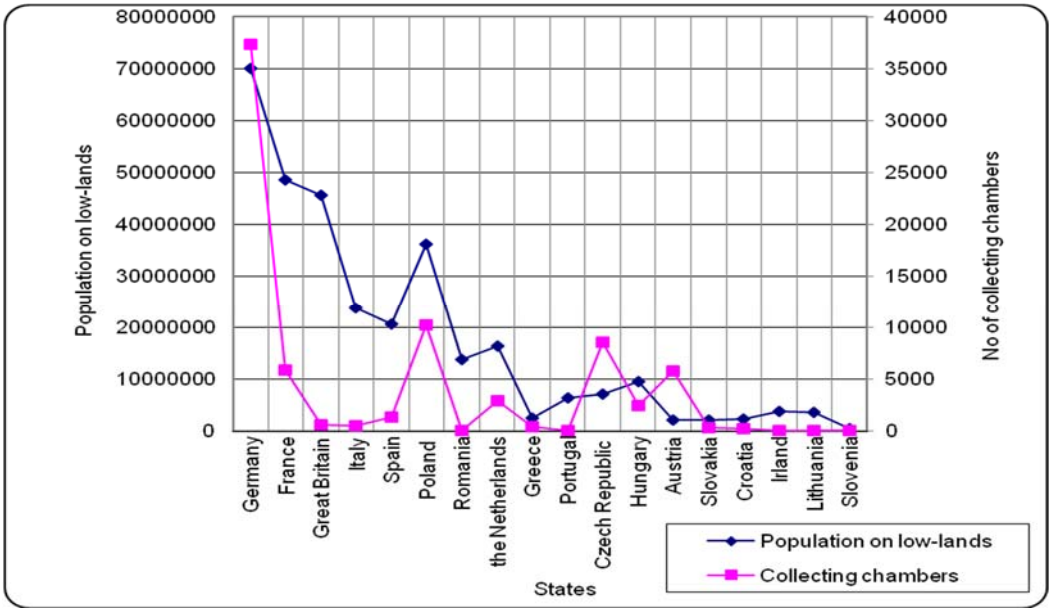


Figure 4. Relation between the population living on low-lands area and number of collecting chambers

The study concludes that the rate of adoption of eco-innovation reduces as the level of saturation is achieved; the early adoption states have a higher level of eco-innovation adoption than the new-comers, even though the last ones can enjoy the leaps over certain stages in the development of a product in comparison with early adopters; the geographic proximity influences what states represent the early or late adopters; the geographic conditions shape the patterns of eco-innovation adoption. The results illustrate that the general economic performance measured in GDP does not influence in a direct way the adoption of eco-innovation.

From a point of view of EMT doctrine, the adoption of eco-innovation represents an important pillar in attaining sustainability. The case study concludes that the ecological modernisation it is proportional with the number of projects implemented, the states of the former Communist Bloc, being situated in diverse stages of socio-economic development reported to development states, evolution generated by the vicinity conditions and less by the GDP.

As Jänicke (2000, 2006) stated the changing of the direction of technological development towards less polluting solutions in terms of innovation and its diffusion represents an active commitment towards the environmental protection, essential for the eco-innovative markets.

The mechanisms of the market are crucial, facilitating the emergence and diffusion of new environmental technologies, aspects approached in this scientific research.

The survey findings on eco-innovation supported the first research hypothesis, concluding that there was a descending trend in adopting eco-innovation from the time of the introduction of the innovation on the market until the third stage of adoption (Beise, 2001; Beise and Rennings, 2004; Costantini et al., 2015; Epicoco et al., 2014; Ghisetti et al., 2015; González-Moreno et al., 2013). The situation was confirmed mainly for the affluent

countries**.**

The study states that the Eastern European Countries have manifested little inclination for this policy approach due to specific conditions associated with *the remainder of the Iron Curtain ideology, financial constraints and a still-weak presence* or late penetration of the green markets and technologies in wastewater collection. Despite the process of national catch-up growth, the central and eastern European states' economies that are centred on bureaucratic management are still in a phase of development and restructuring, lagging in areas including innovation and its adoption (Ezcurra et al., 2007; Longhi et al., 2004; Monastiriotis, 2011), but the area still enjoys updated technology. From this perspective of the market structure effect, the second research hypothesis cannot be totally supported, concluding that there is not a direct obvious relationship between technological catch-up and economic performance. In these particular cases, we correlated our findings with third hypothesis that postulates the existence of a direct relationship between the level of innovation and neighbourhood conditions that accelerate the adoption of a new innovative technology.

Even though, in general terms, the economic performance influences the uptake of innovation, whenever, as the case study demonstrated, some countries with a medium or small GDP level have experienced a higher uptake of innovation, due to vicinity conditions with the lead market and transfer of information through diverse channels. This trend is also correlated with the saturation of the market in the most advanced economies.

From the perspective of the final recipients of the sewer system reported to the population living in the low-lands area, the study concludes that Austria and Czech Republic, outrank Germany, the main European producer of vacuum sewer system. Therefore, the hypotheses 4 cannot be proved. There is not a direct relation between the total low-land area, number of inhabitants of a state and the number of sewer projects,

Based on theoretical framework and a specific research case study this paper showed that the barriers to radical innovations adoption can be overcome within particular trajectories in an evolutionary way. In the present study, the changes in the adoption rate of eco-innovative technologies over time explain the gaps between the developed and emerging economies. The study also brings critical reflections and windows of opportunity for the later adaptors to incorporate the most advanced technologies in comparison with the pioneer states.

One of the main limitations of this study is that the research focused only on two main vacuum sewer system producers, and hence the results over the adoption of vacuum sewer system cannot be considered representative for the whole vacuum sewer industry. Another limitation concerns the data basis provided by our respondents concerning the number of projects implemented in the period 1973-2008.

Despite these limitations, this study has several implications for research, policy and management arena. The findings of this study contribute to the literature on the adoption of eco-innovations

While vacuum sewer system represents a key mechanism for greening of sanitation system, the economy, market dynamics and the social context, are significant carriers for ecological reforms. Considering the poor economic performance of low profile countries in

what concerns the diffusion of innovation, suitable measures for strengthening the institutional capacity to induce the introduction of technological innovation is a path towards ecological modernization of the wastewater system. In matters of wastewater collection, the vacuum system is still an eco-innovative solution for Eastern European countries.

Overall, our study has added a small but relevant stream of research on adoption of eco-innovation of public goods focusing on driving forces that stimulate or impede eco-innovation, especially in emerging economies going through institutional transitions. Moreover, the study has impact on the traders that are particularly interested in the diffusion process as it determines the success or the failure of the products.

This case study illustrates the importance of applying diffusion of innovation analysis to other green technologies in order to create the best uptake scenarios.

b. Determination of environmental externalities resulted from the collection and conveyance of the wastewater

In order to comparatively evaluate the gas phase emissions stripped into the atmosphere as a result of wastewater conveyance, two case studies were analyzed. The difference between the case studies is given by the transportation mechanism: gravitation and lift stations vs. negative pressure into the system.

Data on technical aspects of the projects were collected from technical studies, from other published studies, catalogs of products, statistics, and from expert opinion.

The main scope of this research work was as follows:

- to identify two alternative technologies for wastewater collection that can be used for sewer gas monitoring;

-to develop a methodology to quantify the main sewer gasses: CH_4, H_2S, CO_2 and CO emissions from wet wells and vacuum station;

-to determine CH_4, H_2S, CO_2 and CO emission factors applicable to wastewater wet wells and vacuum station;

For the case study of conventional sewer system, the sample gasses were analyzed directly from the wet well of lift stations. In what concerns the sewer gasses collected in the vacuum tank of the vacuum system before biofiltration the gasses were collected into a special plastic bag. The reason behind this decision was that the functioning of the analyzer would be damaged due to the negative pressure on the vacuum sewer system. In both case studies, the sewer gas concentrations were measured using a gas analyzer (Biogas 5000) designed by Geotech that samples and analyses CH_4, CO_2, and oxygen content in percentage (%) and CO and H_2S in parts per million (ppm).

The measurements were made for both systems in similar conditions, during summer season (28°C).

The methodology does not differentiate any variations in emission level based on the wastewater characteristics within the wet wells or vacuum reservoir as the final results are aggregated because the method measures actual emissions. The study makes the assumption that the wastewater characteristics for the two case studies do not differ as they concern rural areas without intake of industrial or commercial wastewaters.

Also the study makes the proviso that the emission rates depend on hydraulic retention time within the wet wells or vacuum tank and the presence of absence of oxygen. An increase or decrease in the retention time results in an increase or decrease in the extent of the chemical or biological reaction, therefore higher emission level.

The first case study had the objective to quantify the level of sewer emissions (CH_4, H_2S, CO_2 and CO) by direct measurement of gas flow from four lift stations. The 18 km sewer system collects the wastewater mainly from the residential area and conveys it to a wastewater treatment plant dimensioned at a maximum daily flow of $300m^3$.

The second case study concerns vacuum sewer system. With a lengths of 7 km, the vacuum sewers under negative pressure (-0.6 bar) collect the wastewater from a number of 190 houses. The system is based on the principle of using the differential pressure in vacuum pipelines to collect the wastewater and transport it to a vacuum station, then gradually to a centralized wastewater treatment plant (Airvac Inc., 2015; Buchanan et al., 2010; Deutsches Institut für Normung (DIN), 1996; Roediger, 2015). The vacuum sewer system is represented by the collecting chambers, pressure sewers, vacuum station, and biofilter. The wastewater from vacuum reservoir is pumped into the wastewater treatment plant.

The quantification of CH_4, H_2S, CO_2 and CO collected at the level of vacuum reservoir and exhausted to the biofilter was done by instantaneous direct measurement with the help of a gas analyzer. The measurements were done at the level of exhaust pipe of vacuum pump before biofiltration and at the level of biofilter.

The study approaches the problem of production of sewer gases resulted from the collection and conveyance of wastewater, objective only little approached in the literature (Czepiel and colab., 1993; Denman and colab., 2007; Foley and colab., 2009; Foley and colab., 2010a; Daelman and colab., 2012, 2013; Lane and Lant, 2012).

The efforts to quantify gas emissions from wastewater handling have omitted the conveyance along sewers, lift stations and manholes. The study assesses the value of the conventional vs. vacuum sewer system from a point of view of sewer gas emissions. The goal of the study was to determine by instantaneous sewer gas measurements, the emissions of methane, hydrogen sulfide, carbon dioxide and carbon monoxide at the level of the wet-wells of conventional wastewater system vs. the exhaust system of the vacuum system before and after the bio-filtration process.

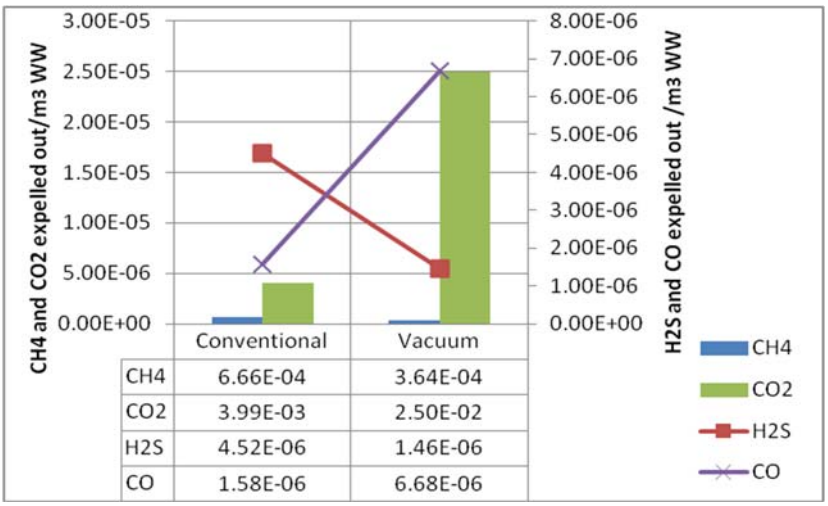
The comparative analysis of the gas emissions at the level of the two systems demonstrated that the emission level of methane in the case of conventional system is 1.83 times higher than of the vacuum system. The hydrogen sulfide emissions in conventional system exceed 3.09 times the level of the same gas in vacuum sewer system, while the carbon dioxide and carbon monoxide are 6.24 times, respectively 2.40 times higher in the vacuum system (Figure 5).

The study concludes that the biofiltration for the vacuum sewer system can be regarded as a supplementary measure to compensate eventual breaks-down of the system. For the specific case study the measurements performed at the level of exhaust pipe proved that the emission level it is low, some parameters after biofiltration exceeding the values measured before biofiltration.

It can be observed from the Figure 1 that the hydrogen sulfide emissions per unit of

volume in conventional system exceed 3.09 times the level of the same gas in vacuum sewer, while the carbon dioxide and carbon monoxide are 6.24 times, respectively 2.40 times higher in the vacuum system.

Figure 5. Comparative analysis of emission per unit of volume- conventional vs. vacuum sewer system (emissions per m^3 WW)



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The results of the study are based on the evidence that in the rural areas there are periods of time when there is no flow in the piping system and some segments are "stagnant". In this situation, the biomass continues to accumulate as the biomass on the piping system and wet well walls reproduces. The low wastewater flow due to reduced number of connections and consumption in rural areas comparison with the designed situation means that the wastewater often stays in the piping system and lift stations for many hours. This means a very high hydraulic retention time (one day as in the case of Lift Station 1 and Lift Station 3), which results in a total depletion of oxygen within the conventional sewer system. The lack of oxygen it is followed by the production of foul odors and large quantities of hydrogen sulfide gas. When the wastewater is moving slowly or not at all, the hydrogen sulfide gas produced by sulfate reducing bacteria accumulates in the wet wells.

The difference in criteria pollutant emissions between the two systems scales closely with the difference in operational model associated first of all with the aeration of the wastewater at a ratio of 1:5 (wastewater: air), high velocity of wastewater during conveyance and short residence time of water in vacuum reservoir within the vacuum sewer system.

Despite the higher overall efficiency of vacuum sewer system, the research shows the need to replace the biofilter media in a regular basis (two years) to reduce the sewer emissions.

The emissions for the conventional system case study exceed the level of emissions in vacuum sewer system due to high retention time of the wastewater in lift stations as a result of reduced number of connection compared with the designed situation, and the need to increase energy consumption for more frequent wastewater pumping, leading to a higher tariff for energy.

In this respect this study proposes the filtration of the air from the wet-wells of pumping stations in biofiters by retrofitting the lift stations with installing fans and air ducts to exhaust the air into biofilters. The limitations of this engineering method for treating the sewer gas are connected to the location of the lift station in the proximity of the road and private property rights over the adjacent plots of land.

The volume flow of gas treated by one square meter of biofilter surface (specific load of biofilter), is typically expressed as m^3 /m^2 of filter surface/hour. This design parameter may vary over a range of 100 to 400 Nm^3/m^2/hour (IPCC, 2003).

Even though there is a shortage of published articles on the comparative emissions level for wastewater collection technologies, the analysis of the case study provides evidence to support the hypothesis that the vacuum technology can succeed in reducing the carbon footprint by reducing the level of methane that made the subject of the present research. In what concerns other analyzed gasses it was observed that the level of hydrogen sulfide was reduces, while the level of carbon dioxide and carbon monoxide increased.

Compared with other studies that emphasized the gas phase methane concentrations varying from 500–900 ppmv of up to 50,000 ppmv detected in the air of a gravity sewer (Shah et al., 2011; Liu et al., 2014; GWRC, 2011;) the present research quantified gas phase methane concentrations of 2,000–2,500 ppmv in the lift stations and 330 ppmv before biofiltration and 1,000 ppmv after biofiltration in vacuum sewer system.

Hydrogen sulfide concentrations registered values that exceed the maximum accepted contaminants level of 1ppm (3-4ppm for conventional system). The vacuum sewer system evinced average measured concentration of H_2S of 0.33ppm, below the maximum accepted contaminants level.

In what concerns the values of CO_2 and CO, the results of instantaneous measurements indicate that the emissions of CO_2 and CO are higher for the case study of vacuum sewer system. The explanation for the higher CO_2 level resides possibly on the functioning of the vacuum pumps that are lubricated with oil and the oxidation of sewer gasses to CO_2 and water in biofilter. CO it is under the average accepted level in buildings (0.5-5.5 ppm) (EPA, 2015) and can also result from the exhaust of internal combustion engines of the vehicles.

As demonstrated by the field data collected as part of the instantaneous measurements, the wet wells can be an important source of CH4 and H_2S emissions. Emissions estimate for the conventional wastewater system based on instantaneous readings underreports the actual emissions, first of all, due to hourly variations in wastewater flow, retention time in sewers and wet wells, and stripping off some gasses during the lifting up of covers for two of the four lift stations.

For more accurate prediction of CH4, H_2S, CO_2 and CO production from the wet wells, continuous monitoring is recommended. Moreover, a way of reducing the emission level is to consider the minimization of the residence time of the wastewater in the wells. This can be done considering the reduction of time interval between two pump runs that on the other hand, increases the energy consumption with impact on the emission of GHG. All four wet wells exhibit higher hydrogen sulfide levels which pose corrosion risks to the wastewater infrastructure.

Sewer gas monitoring of wet wells can help estimate the emissions from point sources within the conventional wastewater collection system. However, there is no acceptable method or mathematical model of estimating emissions from the entire sewer network, including the sewers and manholes.

According to our results, the retention time and lack of oxygen is directly proportional to the emission rate.

Besides analyzing two case studies with different technologies for wastewater collection with a focus on the current and potential emission level based on sewer gas emission measurements, this research shows the need to provide a framework for further analysis that is essential for the promotion of eco-innovative technologies for wastewater collection. Wastewater system planning needs more robust sewer gas emissions analysis when implementing projects for wastewater collection.

This study evaluated the sewer emissions for two different transportation mechanisms for wastewater collection, providing a different perspective on the pro-active technologies for avoiding and reducing the air emissions from wastewater collecting systems. The approach described herein provided a framework for deciding if the vacuum technology can succeed in reducing the carbon footprint and foul odors by reducing the level of methane and hydrogen sulfide in a comparative basis with the conventional wastewater system. While the analysis is based on a simple methodology for sewer gas measurements and the construction of a mathematical model for emissions estimation, it is obvious that some benefits occur when look from an environmental perspective to the vacuum sewer system.

c. Economic evaluation of alternative wastewater collection systems

The aim of this study was to investigate new perspectives with respect to the greening of the wastewater collection, subsequently assessing the value of the vacuum over the conventional wastewater collecting system in rural areas.

The research was framed from the perspective of policy makers to aid in making decisions about benefits on long term horizon in implementing eco-innovative infrastructure technologies. The study postulates the hypothesis that the vacuum sewerage system is technologically, environmentally, economically and socially more sustainable in comparison with the classical solutions for the wastewater collection. Economics provides a powerful tool for helping solve environmental problems.

A comparative analysis between two variants of the same project considering vacuum and conventional sewerage technologies was performed, by using as input for current research the Cost-Benefit Analysis. The analysis focuses on a simulation of a particular territorial context, the case of flat land rural areas in Romania.

The section tried to analyze all the issues affecting the comparison between the vacuum technology and classical technology with pumping stations with solids separation.

Several stages were conducted: defining the project, identifying impacts which are economically relevant, physically quantifying impacts, calculating a monetary valuation, discounting, weighting and sensitivity analysis (Hanley and Splash, 2003).

Cost benefit analysis starts from the premise that a project is feasible only when the

aggregated benefits exceed all costs. Whenever, it is well known that wastewater collection and treatment it is a feasible process mainly from the point of view of positive environmental externalities as we deal with proving a public good. The study poses that the most efficient wastewater collection process is the one that minimizes input consumption (energy) and undesirable output generation (smell and pollution generation, leakage) while minimizing the operating and maintenance costs.

In order to evaluate the financial attractiveness of a project alternative against the other, the Net Present Value and Internet Rate of Return techniques were used. Both techniques emphasize the importance of the concept of the time value of money.

The international methodology of financial analysis of the project on a cash flow basis suggests conducting the financial analysis and the calculation of the investment returns using the total cost of the investment.

In order to evaluate the financial attractiveness of a project against the other, the Net Present Value and Internet Rate of Return techniques were used. The most important indicators for the two sewerage systems are presented in Tables 1 and 2.

Table 1. Key performance indicators for the vacuum sewerage alternative

Key performance indicators	Value	Permissible value
Investment costs	1,392,259.13	
NPV	-1,134,321.32	≤0
IRR	-6.90 %	≤5%
Cost benefit ratio	0.73	<1
Cumulative cash flow	Positive every year	Positive every year

Table 2. Key performance indicators for the classical sewerage alternative

Key performance indicators	Value	Permissible value
Investment costs	1,358,797.06	
NPV	-1,114,957.86	≤0
IRR	-7.07 %	≤5%
Cost benefit ratio	0.78	<1
Cumulative cash flow	Positive every year	Positive every year

In the absence of funding constraints, the best value for money projects is that with the highest NPV. The negative values of NPV within the two alternatives of sanitation projects, where the main aim is to satisfy social and environmental requirements, draws on the necessity the projects is co-financed. The IRR is smaller than 5% (the recommended discount rate).

The cost benefit ratio (CBR) is bellow 1, meaning both projects are viable. For each euro invested in the vacuum sewerage project, 0.73 € is saved (CBR = 0.73). Whenever, for each euro invested in the classical sewerage project, 0.78 € is saved (CBR = 0.78). On the other hand, as was discussed before, when looking at externalities, the vacuum sewerage system brings more savings due to the reduction of raw sewage discharges because of spillage in the wastewater network. These benefits represent in fact the avoided monetary

losses expected to accrue as a result of implementation of one project or another.

Tracing costs and benefits sheds new light on the innovative technologies for wastewater collection. The analysis of the case study provides evidence to support the hypothesis that the vacuum technology can succeed in overcoming the environmental crises by internalizing the externalities, having the capacity to improve environmental factors, reduce energy and maintenance costs. Besides, this research shows the need to provide a framework for further analysis that is essential for the promotion of eco-innovation and reflexive institutions.

The research shows the difference between vacuum sewerage technology and conventional technology, in terms of costs, environmental and social benefits. Even though there is a shortage of published articles on the wastewater collection technologies and their environmental impact, the analysis of the case study provides evidence to support the hypothesis that the vacuum technology can succeed in overcoming the environmental crises by internalizing the externalities, having the capacity to improve environmental factors, reduce energy and maintenance costs.

On the one hand, the results showed in this research are based upon a technical analysis of energy consumption. Despite the higher overall energy efficiency of both wastewater collection solutions, the vacuum technology brings more energy savings and consequently reduced greenhouse emissions.

Water quality is measured in terms of biochemical oxygen demand (BOD_5). Having a low level of BOD_5 in wastewater is essential to avoiding penalties and producing high-quality effluent. If the amount of pollutants leaving a wastewater collecting system is too high, or the discharge endangers public health or the environment, the facility may violate its permit and can be fined or required to upgrade.

On the other hand, the environmental externalities were estimated (BOD_5 and SS) and wastewater leakage occurrence was used in calculating the amount of main individual pollutants discharged into the environment that makes the difference between the two design variants of the sewerage system, showing greater benefits in implementing the vacuum technology.

The environmental benefits, expressed in monetary terms, have been calculated. They reflect the value of environmental damage avoided derived from wastewater collection or an environmental benefit. In this regard, we considered the probability of sewer seepage occurrence in both alternatives. According to the expert opinion, in the classical wastewater system, the sewer leakage can reach 10 % of the volume of raw wastewater, with difficulties in decelerating the sewer line break, manholes or pumping stations which allows wastewater seepage. In the vacuum system, this probability is much reduced due to negative pressure in the system and possibility of detecting the leakage because of monitoring system, reaching 1% of the total wastewater running into the system with rapid intervention on the specific sector with sewer line break.

The financial value of avoiding further pollution is emphasized in Table 3.

Table 3. Quantification of the wastewater seepage from the wastewater network

Parameter	Quantity (kg/year) x value of penalty (€/kg)	
	Vacuum system	Classical system
BOD_5	0.003 · 204.51 = 0.61 lei	0.06 · 204.51 = 12.27 lei
SS	0.003 · 25.56 = 0.07 lei	0.07 · 25.56 = 1.79 lei

Besides analyzing the current and potential developments and creating knowledge about the environmental costs and benefits of a sewage system construction and operation, this research shows the need to provide a framework for further analysis to quantify the level of greenhouse gases released as a result of functioning of alternative wastewater collecting system, that together with the quantification of wastewater seepage into the soil and groundwater, is essential for the promotion of eco-innovation and reflexive institutions.

In order to overcome some recognized CBA limitations, a method to quantify the environmental impacts was developed. In our specific case, despite commonly relied upon metrics to communicate benefits to decision making, the CBA was used to formulate economic arguments for investing in risk reduction, rather than responding to the future impacts. The positive externalities associated with avoiding the discharge of pollution into the environment made the subject of the study.

By adopting more stringent and innovation oriented regulations, environmentally proactive bodies will be more capable of facing the challenge of an accurate internalization of environmental effects and reduce negative environmental impacts (Ferrón-Vílchez, de la Torre-Ruiz, and de Mandojana 2013). It may also be worthwhile to take the societal perspective, which would include benefits to tax payers for wastewater collection and improved quality of life. Unfortunately, the problem of tariff setting for sanitation deviates from the optimum economic, that is why the opportunity costs of the service are not visible, being very small in relation with the financial costs (Rogers, de Silva, and Bhatia 2002). Due to the public good character of sanitation this aspect creates inefficiencies in providing the sanitation services.

The approach described herein provides a framework for deciding if the supplementary investment costs for vacuum technology is commensurate with the potential benefits. While the analysis is based on a simple methodology for cost benefit analysis, and somewhat uncertain data concerning the willingness to pay, it is clear that some more benefits accrue when look from an environmental perspective.

Research shows that the increase of the additional benefits accruing from additional provisions in the design and operation of infrastructure is directly proportional with the technological improvements being brought to the system.

d. The analysis of wastewater collection systems resilience

Another objective of the study consisted in making a comparative analysis of alternative wastewater collection projects exposed to sundry natural and anthropic disruptions from the perspective of resilience concept *(Resilience Alliance, 2007; Saaty, 1996a; Saaty 1996b; Saaty and Vargas, 2006; Saaty, 2008).*

The construction of Analytical Network Process was built starting from the following question: Which alternative of wastewater collection presents the highest risks from an environmental, economic and technological point of view?

The selected criteria are used to evaluate and compare the two alternatives having the view the selection of that wastewater system with highest resilience. The criteria are non-redundant and independent and are represented by economic, technological and environmental indicators (risks).

- *Economic indicators* (measure economic resilience), derive from the budget of the projects and cost-benefit analysis, and are represented by the cost of investment, energy cost and maintenance cost;
- *Technological indicators* (measure technological resilience), derive from the experience of researcher, technical guides, standards, and are represented by the security in the exploitation of the two wastewater collection;
- *Environmental indicators* (measure environmental resilience), derive from emission measurement, appreciation of quantity of materials and works, equipments and fuel necessary for the implementation of the two alternative projects.

The model of analysis was build with the software *Super Decisions v 2.6.0-RC1* (www.superdecisions.com). The aim was to determine what is the system that involves the highest risks, therefore a lower degree of resilience. The entry data allowed that the personal judgments concerning the pairs of elements to be examined graphical (histogram), on matrix or questionnaire.

The case study concludes that from the point of view of design and operation in normal conditions, without the pressure of external factors as natural hazards or anthropic hazards, the vacuum sewer system exhibits a reduced risks when compared with classical wastewater collection system with lift stations. Moreover, the study was also framed for the functioning of the system under exceptional conditions (earthquakes, landslides, flooding), that involves major pressures on the objects of the wastewater infrastructure. At holistic level, the comparative analysis of the two systems from the point of view of resilience attributes (robustness, redundancy, innovative character, and rapidity) and of main types of vulnerabilities (technical, economic and environmental) highlights that the vacuum sewer system presents a higher degree of resilience.

The study proposes the incorporation of the concept of resilience within the larger concept of ecological modernisation that implies a general vision of economic development through the integration of environmental concerns into business as usual, by internalizing of the environmental concerns into the design and production process.

The proposed approach in this scientific research, by adopting the resilience of

infrastructure as a new pillar of ecological modernisation (economic, technological and institutional reform), integrates another two aspects: capacity of fast recovering following different types of disruptions and the economic, social and environmental reliability of infrastructure investments (Figure 6).

While the resilience focuses on preoccupations for management of disruptions when confronting with natural or anthropic hazards, towards a greater redundancy of the systems, additional resources as backup solutions, the ecological modernisation is focusing on the efficient use of resources to maximize profitability while reducing the pressure on the environment and restoring economic and environmental systems in a state of balance.

The integration of resilience in the EMT represents a window of opportunity to counteract the forecasted climate change, but also extreme events (earthquakes, flooding) on the infrastructure by understanding the need to restructure the policies in the field of water and wastewater management and planning process.

The urban planning and development of new wastewater collection technologies support the adaptation of infrastructure to multiple categories of adverse impacts, not only to the climate change, therefore the investment decisions have to be taken considering these challenges thus to reduce risks at minimum.

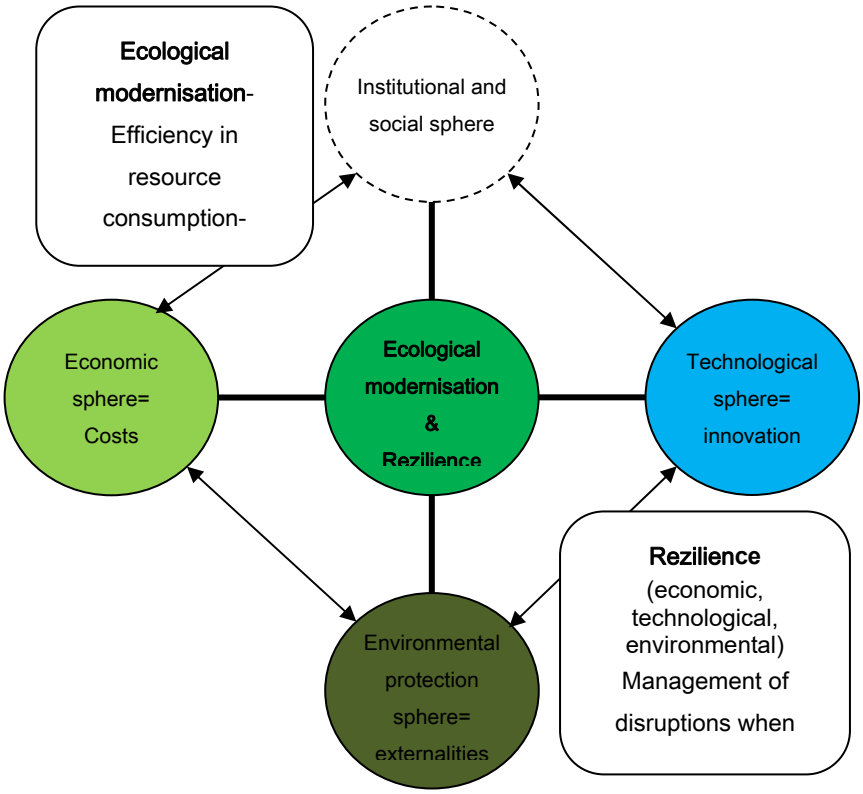

Figure 6. Integrative model for the presentation of new concept of ecological modernisation and resilience

5. General conclusions

Theoretical conclusions concerning the analysis of ecological modernisation of the wastewater infrastructure

The study explored the environmental and financial implications of transition towards an eco-efficient and resilient infrastructure both from economic perspective and carbon footprint perspective by means of reducing the level of direct and indirect emissions of sewer gases (hydrogen sulphate and GHG), but also from a point of view of the natural and anthropic pressures and of the impact and associated risks on other infrastructures as water supply, transport, housing and socio-economic objectives.

The EMT is seen within this scientific research as an opportunity to reduce the economic and environmental impact associated with the implementation of alternative wastewater systems within villages or small towns placed on lowlands. EMT has the advantage that can indicate that the sustainability can be attained through reconciliation of environmental and economic objectives by means of super-technologisation and innovative technologies that mitigate the environmental impact of socio-economic development.

The thesis proposed a technical, engineering approach of ecological modernisation in the field of wastewater management, overcoming its theoretical limits, that was used mainly in a sociological way, in order to conform or refute the capacity to overcome the ecological crisis in the field of environmental strategic planning.

Ecological modernisation concept is nowadays on many country policy agenda. To talk about a paradigm change in what concerns the scientific justification to declare ecological modernisation a change in environmental practices towards the ecological industrialisation (*Spaargaren and Mol, 1992; Cohen, 1997a; Spaargaren, 1997)*, in order to get a more practical value of the concept it was necessary to introduce specific instruments to measure the level of ecological modernisation beginning with the design and planning process.

The thesis points out on the capacity of eco-innovative technologies to contribute to the greening of wastewater collection systems. In this respect, the analysis of economic and technological reform in evaluating two alternative wastewater collection systems highlights the environmental and economic benefits generated by the adoption of radical innovations as it is the vacuum sewer system. Thus, the case study proves that the implementation of advanced technologies can be seen as a measure to overcome the environmental crisis, through the internalization of externalities. The study concludes that eco-innovative technologies of water collection fit in the general paradigm of ecological modernisation. The study does not have the objective to put in a bad light the alternative technologies that proved their important role in the wastewater collection, but it emphasizes, reported to land conditions, on the benefits of vacuum sewer implementation when consider two projects implemented on flat land on small rural areas.

The gradual reduction of fossil fuels and consequences regarding the climate change should contribute to the change of attitude towards the energy consumption. Consequently, it

is necessary to introduce both environmental and resilience criteria in the processes of decision making.

Innovative infrastructure projects (vacuum sewer system) that answer the resilience attributes have the capacity to face and adapt the challenges of operation in normal conditions, but also under the pressure of climate change and other extreme events (natural and anthropical disasters).

The thesis proposes the incorporation of resilience as a new pillar of the larger concept of ecological modernisation.

The results of research serve as a basis for the decision making process in the prioritization of intervention areas and introduction of eco-innovation in the field of wastewater collection.

In this context, the green procurement policies can serve as management practices for the local councils or wastewater collection operators that want to ensure competitive services by adopting technologies.

The study concludes that the engineering can play an important role for the enforcement of ecological modernisation; therefore, this area can be considered the engine of ecological modernisation. The technical expertise of designing organizations and of suppliers of eco-innovative technologies can contribute it is a source of know-how for the decision makers on the planning infrastructure opportunities.

6. Originality of the thesis

The most important contribution it is of methodological nature and consist in a combination of methods and techniques derived from diverse disciplines in order to develop a uniform set of instruments to measure the degree of ecological modernisation of two alternative technologies of wastewater collection. The proposed methods are based on a set of techniques of analysis of EMT that can be replicated for other case studies.

The thesis approaches aspects that have not been reported in the literature:

- ranking states, including Romania, in the hierarchy of the world states that have adopted eco-innovative technologies for wastewater collection (vacuum sewer system) with a focus on the trends and factors that stimulate or impede the eco-innovation diffusion;
- analyzing alternative wastewater systems in terms of negative externalities, namely sewer gasses and hydrogen sulfide and greenhouse gasses. Designing a methodology for analyzing the emissions of sewer gasses at the level of classical and vacuum sewer system and calculation of emission factors for main sewer gasses.
- cost-benefit analysis of two alternative wastewater collection systems with a focus on the financial evaluation of externalities (exfiltrations of wastewater);
- comparative analysis from a point of view of resilience attributes of two alternative wastewater systems (classic versus eco-innovative)
- suggestion of incorporating the resilience concept within the paradigm of ecological modernisation.

Included papers and the contribution of the researcher in the topic of dissertation

Articles published in ISI indexed magazines and proceedings

1. **Terryn I.C.C.**, Lazar I., Nedeff V., Lazar G., (2014), Conventional vs. vacuum sewerage system in rural areas - an economic and environmental approach, Environmental Engineering and Management Journal, **13**, 1847-1859
2. **Terryn I.C**., Lazăr G., (2016), Driving forces affecting the adoption of eco-innovation: a survey on vacuum system, Environmental Engineering and Management Journal, **15** (3), 589-598
3. **Ciobotici Terryn I.C**., Cocarcea Rusei A., Stamate M., Lazăr I., (2016), Eco-innovative technologies for mitigating gaseous emissions from wastewater collection systems, Environmental engineering and management journal, 15(3), 613-625

Articles submitted to be published in ISI indexed magazines

1. **Ciobotici Terryn I.C**., Cocarcea Rusei A., Lazăr G., (2016), Mitigation of hazardous air polutant emissions: vacuum vs. conventional sewer system

Articles published in ISI proceedings indexed magazines

1. Bănică, Al., Breabăn I.G., **Terryn I. C.**, Munteanu A., (2016), Vulnerability and resilience of the urban drinking water system in the City of Bacău, Romania, 3rd International Multidisciplinary Scientific Conference on Social Science & Art – SGEM 2016, 24030 August 2016, Albena, Bulgaria, Conference proceedings, book 1, Phychology & Psiychiatry, Sociology & Healthcare, Education, volume II, 1209-1217, ISBN 978-619-7105-71-1, ISSN 2367-5659, DOI 10.5593/sgemsocial2016B1

Chapters in books:

1. **Terryn I.C.C, (2015)**, Peformanța sistemului de canalizare în vacuum din perspectiva unei infrastructuri reziliente, în Bănică A. and Muntele I, (2015), Reziliență şi teritoriu, Operaționalizarea conceptuală and perpective metodologice, Editura Terra Nostra, Iaşi, 2015, ISBN 978-606-623-056-8, pag. 137-151.

Presentations in the framework of National and International Conferences

1. **Terryn Iulia Carmen**, Lazar Iulia, Nedeff Valentin, Lazar Gabriel, Conventional vs. vacuum sewerage system in rural areas - an economic and environmental approach, The 7th International Conference - Environmental Engineering and Management – Integration Challenges for Sustainability, 18-21 September 2013, Vienna, Austria.

2. **Terryn Iulia Carmen (Ciobotici)**, Cocarcea Rusei Andreea, Stamate Marius, Lazăr Iulia, Eco-innovative technologies for mitigating gaseous emissions from wastewater collection systems, Second Internaţional Conference on Natural And Anthropic Risks, 4-7 June 2014, Bacau, Romania

3. Andreea Cocarcea (Rusei), Gabriel Buftia, **Iulia Terryn**, Marius Stamate, *Design of labbiogas installations from recycled materials*, The XIth International Conference OPROTEH, 4-6 June, 2015, Bacau, Romania;

4. **Terryn Iulia Carmen (Ciobotici)**, Cocarcea Rusei A., Lazăr G., Mitigation of hazardous air polutant emissions: vacuum vs. conventional sewer system, The 8th International Conference - Environmental Engineering and Management, 8-12 September 2015, Iaşi, România.

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