

A Systemic Conceptual Model to Support Decision-Making in the Sustainability Assessment of Industrial Ecosystems

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Abstract. One of the main challenges for companies is to operate in a sustainable way, that is, by protecting the ecosystems where they are located. As a result of such a challenge, different tools and models have been developed to assess their environmental impact and to help decision makers to define strategies to become more sustainable. However, most of these tools have concentrated on the internal parameters of the companies and have failed to assess the actual impact caused on the ecosystem. Therefore, this article proposes a conceptual model to analyze the environmental risks from companies and evaluate their impact on their ecosystems. Results obtained are: 1) a methodology to assess environmental risks and their impact on the environment and 2) a causal loop diagram that identifies the relationships between the industries and its environment, showing that the company's production rate is the key variable, since it determines the amount of both resources consumed and pollutants emitted, so its balance must be achieved in order to preserve the environment, which, otherwise, will collapse.

1 Introduction

Growth in population and economic activities – such as agriculture and industrialization – has negative effects on the environment. Therefore, preserving the balance in the exploitation and use of natural resources is crucial to avoid that such growth becomes unsustainable [1]. From this perspective, society, government institutions, and the industrial sector play crucial roles [2]. However, as regards industries, they are prominent actors because of three reasons [3]. First, as producers of goods and services, they are fundamental to satisfy the needs of both actual and future generations. Second, companies are vital to the economic development and wealth of regions. Third, their processes deteriorate the environment and contribute to the depletion of its natural resources.

Recent statistical data have revealed that the demand of natural resources such as water [4] and energy [5], from companies is increasing and will continue to increase. Such increment often exceeds the capacities of these resources to regenerate, not to mention that it also causes the emission of a greater amount of pollutants [6, 7].

Moreover, according to the World Water Assessment Programme [6], if companies maintain their current habits, by 2030, the world will face a 40% global water deficit.

This situation reveals that a robust approach must be adopted by industries in order to integrate sustainability into their processes and activities through concrete strategies and actions. Such an approach requires tools to assess the sustainability of these organizations [8] and to help decision and policy makers define the actions needed to reach a more sustainable status [9, 10].

According to the literature, the major progresses in industrial sustainable development have been achieved through eco-efficiency based tools [11, 12]. Unfortunately, these eco-efficiency based tools do not seem to provide positive results, since strategies employed merely evaluate parameters inside the company and do not consider the impact caused beyond the operational limits [3]. This implies that new approaches must be developed, and they must allow for a systemic analysis to measure the effectiveness of solutions proposed [13].

The main contribution of this research is therefore a model to assess the sustainability of companies from a systemic approach. The central part of such a model is the analysis of the interactions between the industrial sector and its environment based on water consumption, energy consumption emissions of air pollutants, and emissions of water pollutants. Such factors of environmental impact were selected due to the increasing consumption of water and energy and the high levels of hazardous substances emitted (section 3.1). Likewise, system dynamics (SD) was used to evaluate the model, since such a methodology enables to model different types of systems from the structural analysis of their variables, and this helps understand how systems work and the consequences that may arise from their status [14, 15].

As for the structure of this paper, the remaining sections are organized as follows. Section 2 provides an analysis of the most used tools and SD models for sustainability assessment in companies. Section 3 describes the proposed model in this research, while section 4 defines the methodology followed for its application. Eventually, section 5 introduces the causal loop diagram that depicts the interactions between the key variables from the conceptual model. Finally, section 6 presents conclusions and remarks for future work.

2 Tools for Industrial Sustainability Assessment

In the literature, a great number of industry-related sustainability assessment tools have been proposed and classified in various categories [2, 9, 16]. For example, [9] classified 48 tools in six categories: 1) individual/set of indicators, 2) composite indices, 3) socially responsible investment indices, 4) material and energy flow analysis, 5) life cycle analysis, and 6) environmental accounting. Likewise, [2] evaluates 16 tools, initiatives and methods for corporations to engage with sustainability. However, the analysis conducted to these tools shows that they do not appropriately reflect the damages caused to the ecological processes of ecosystems or the risks that such damages represent for the further development of companies, due to the fact that are focus on process or products. Tools such as SD, multi-criteria analysis, risk analysis, cost-benefit analysis and environmental impact assessment, allow supporting decision

making in sustainability assessment and have the potential to analyze the industry-ecosystem relations, although these tools are not only used for industrial purposes.

Thus, the characteristics that a tool must have to evaluate the environmental impact from companies are the following [3, 8, 11]:

- 1) **A holistic approach** to analyze as a whole all the elements comprised in the industrial and ecological systems.
- 2) **A large spatial scale** to adopt regional, national, and international scales without limiting to processes, plants, or products.

Table 1 shows the analysis of the mentioned characteristics in SD, multi-criteria analysis, risk analysis, cost-benefit analysis and environmental impact assessment. For instance, multi-criteria analysis, risk analysis and environmental impact assessment can employ large spatial scales, but they lack a holistic approach. From a different perspective, cost-benefit analysis does not rely on any of the three aforementioned characteristics, while SD includes them all, because it focuses on analyzing the relationships among the variables of the systems and allows for the use of different spatial scales [15, 17, 18]. Therefore, it is employed by this research.

Table 1. Characteristics of the sustainability assessment tools.

Authors	Tools	Characteristics	
		Holistic approach	Spatial scale
[17–19]	SD	X	X
[20–22]	Multi-criteria analysis	-	X
[23–25]	Risk analysis	-	X
[26, 27]	Cost-benefit analysis	-	-
[28–30]	Environmental impact assessment	-	X

2.1 SD Models for Sustainability Assessment

SD has been widely used to develop simulation models for sustainability assessment in different environmental, social, and economic systems [31].

In the literature several models holistically present the relationships that exist between environmental and socioeconomic systems, assessing the impact of domestic activities on water availability and quality [15, 32–36]; as well as on energy consumption and emissions of CO₂ [37–41].

As for industrial simulation models, they have been applied to a wide range of industries, including the oil and gas sector [42], the automotive industry [43], the cement industry [44, 45], the steel industry [46], and the electric power industry [47]. Such models measure the use of natural resources and the emissions of hazardous substances, although they do not assess the impact caused on the environment.

Conceptual SD simulation models have also been proposed in the literature [14, 48, 49]. These models suggest a set of guidelines to construct them based on the three pillars of sustainability (economic, social and ecologic). In this case, the type of

environmental impact assessed depends on the user's criteria and the specific problem that is addressed.

Even though SD enables to model the different effects caused by social and economic activities on the environment, the literature review on simulation or conceptual SD models for sustainability assessment of companies shows that they do not integrate such damages caused to the environment.

3 Conceptual Model for Sustainability Assessment in Emerging Economies

This section analyzes the four environmental impact factors. These elements are part of the conceptual model proposed to evaluate sustainability, and they will be analyzed by means of a diagram that is part of the proposed model.

3.1 Environment and Industrial Impact Factors

Water consumption, energy consumption, emissions of water pollutants, and emissions of air pollutants, are important environmental impact factors [5, 50, 51] that contribute to the damage that the industrial sector causes to ecosystems. Their importance for industries is explained below.

Water consumption. Water is essential to industries because it is used for several purposes such as cleansing, heating, cooling, steam generation, ingredient, among others [6]. However, the rise in production and consumption -produced by population growth, urbanization and industrialization- has produced an increasing demand in freshwater, affecting its availability. Thus, it is a priority for industries to secure their access to the resource, especially in a competing environment. Besides, it is expected that the world industrial water consumption will increase by 400% in 2050.

Energy consumption. The industrial sector uses energy in activities such as product manufacturing, assembling, steam generation, heating, cooling, lighting of buildings among others; and is considered one of the main worldwide energy consumers [5]. According to the Organization for Economic Co-operation and Development (OECD), the amount of delivered energy in the industrial sector is expected to continue growing in the projection period 2010-2040 [52]. As regards the countries that are part of the OECD, the average increase per year is estimated to be 0.4%. However, for non-OECD members, the percentage increases up to 2.3% per year.

Emission of water pollutants. Industrial wastewaters are a serious ecological problem because they contain toxic substances that are hard to treat [4]. In developing countries around 70% of the industrial wastewater produced is dumped untreated into water bodies, due to the lack of proper legal regulations and industrial investment in technology to treat them [53].

Emission of air pollutants. Industrial pollutants released in the air mainly involve carbon dioxide CO₂. Such pollutants derive from the consumption of energy and the industrial processes of the companies [7]. Since the beginning of the industrial revolution, industrial CO₂ emissions have been increasing, as a consequence of the surge in the use of fossil fuels. This tendency is expected to continue in the future despite the expansion in the use of alternative energy sources [54].

3.2 A Block Diagram of the Conceptual Model for Sustainability Assessment

Figure 1 shows the interactions between the company under assessment and the ecosystem, based in the environmental impact factors described above. As observed in Figure 1, these interactions work as follows:

- 1) The environment provides natural resources (water and energy) to the company for its production processes.
- 2) Companies produce goods and services according to the existing demand.
- 3) As sub-products of the production processes, air and water pollutants are generated and released into the environment.

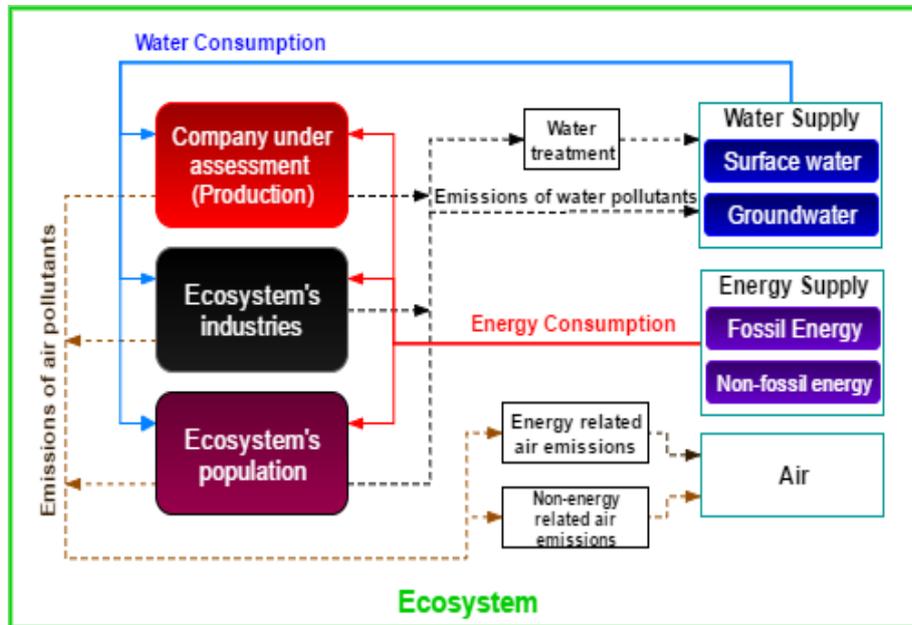


Fig. 1. Conceptual model.

The impact caused on the environment from the industries depends on the amount of natural resources consumed and on the amount of pollutants released and their levels of hazardousness. Thus, in order to improve the sustainability of a company a balance must exist to limit the amount of natural resources that the industry uses and the levels of pollutants that it emits. To guide industrial activities towards a more sustainable performance, one must define ecological limits for the use of natural resources and the emission of pollutants. Such limits ensure the correct functioning of the environment [9, 55], which is severely damaged when companies reach or are close to these limits. Moreover, if ecological limits are exceeded, they will seriously affect the ecological processes, which, in turn, will interrupt the industrial activities of companies involved [56]. Otherwise, companies will be responsible for severe water and energy shortages

and serious environmental degradation. However, a company is not the single actor that damages the environment, since activities from the population and other companies in the same ecosystem also have a negative effect on the environment. Therefore, both sectors are also integrated in the conceptual model.

Finally, it is worth mentioning that this model proposed to assess sustainability enables to know the current status of the environment by indicating the amount of damage caused by the company. From such a result, several strategies can be designed and proposed to diminish damages and guarantee the integrity of the environment and the future of where the model is applied.

4 Methodology Followed to Assess Sustainability

Figure 2 depicts the steps followed to assess the sustainability level of a company. On the one hand, the first stage is the characterization of the company to assess and its natural environment. On the other hand, the second step consists in developing the SD model. Each one of these stages is described below.

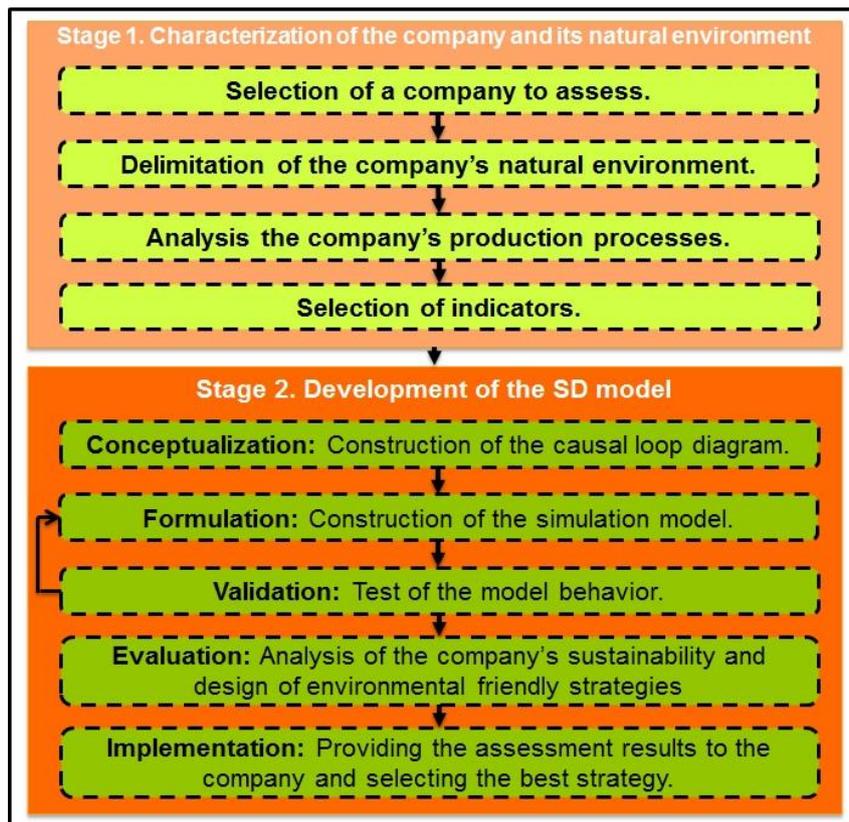


Fig. 2. Methodology to assess industrial ecosystem sustainability.

Stage 1: Characterization of the Company and its Natural Environment

This stage comprises four specific activities:

1. *Selection of a company to assess:* A company is selected to define the level of risk that it poses to the environment based on four factors: water consumption, energy consumption, emission of water pollutants, and emission of air pollutants.
2. *Delimitation of the company's natural environment:* Delimitating the natural environment affected by a company involves identifying: a) sources of supply of natural resources and processes involved in their availability, and b) sources of emission of air and water pollutants and their environmental impact.
3. *Analysis of the company's production processes:* This involves identifying the key processes of the company to determine the amount of both natural resources used and pollutants emitted.
4. *Selection of indicators:* Specific indicators will be selected to both assess the environmental impact of each one of the four factors (water consumption, energy consumption, emissions of water pollutants, and emissions of air pollutants) and define their ecological limits. Such limits will be used as reference to know the level of sustainability of the company.

Stage 2: Development of the SD Model

The model is developed following the stages described by Sterman (2000) and Cedillo-Campos and Sánchez-Ramírez (2008) for the creation of SD simulation models

1. *Conceptualization:* Key variables are selected. These variables represent the different interactions between a company and the environment. They are represented by a causal loop diagram.
2. *Formulation:* The simulation model (Forrester diagram) is developed based on the causal loop diagram. The system's behavior is described by means of mathematical equations related to the following factors: water consumption, energy consumption, emission of water pollutants, emission of air pollutants, generation of natural resources, and damages caused to these natural resources, among others,
3. *Validation:* The model is validated through different tests in order to determine whether its structure and behavior are consistent with the system that it represents [57, 58] (i.e.: the interactions between the industry and the environment). If results from these tests are not satisfactory, corrections must be made.
4. *Evaluation:* The level of sustainability of the company is assessed based on results obtained. Similarly, strategies for sustainability improvement are developed, and their effectiveness is tested. Finally, the most suitable strategy is selected.
5. *Implementation:* Final results are provided to the company and suggestions are offered to implement the most suitable strategy to improve sustainability.

This article presents the first step in the development of a SD model, which is the construction of the causal loop diagram.

5 Causal Loop Diagram

Table 2 lists and defines the variables that compose the causal loop diagram. Let us recall that such a diagram defines the different interactions between a company and the environment (Figure 3; **Error! No se encuentra el origen de la referencia.**). Note that these variables were identified as key elements to assess the impact of the four environmental impact factors (water consumption, energy consumption, emissions of water pollutants, and emissions of air pollutants) over the environment.

Table 2. Variables of the causal loop diagram.

Authors	Variables	Description
[59, 60]	Demand	Amount of goods and services required by consumers.
	Company's production rate	Amount of products to manufacture.
[15, 34–36, 61, 62]	Company's water demand	Volume of water required for the industry's processes.
	Water consumption	Volume of water consumed in the region.
	Shortage	Environmental impact produced when the water consumption exceeds the available supply.
	Water supply	Total volume of water provided by surface and groundwater sources.
	Surface water	Volume of water withdrawn from superficial sources.
	Ground water	Volume of water withdrawn from groundwater sources.
	Company's emissions to water	Volume of wastewater produced by the company.
	Pollutant load	Degree of pollution of wastewater.
	Water quality	Measure of the water's physical and chemical properties that indicates the environmental impact caused to the resource.
	Company's water quality requirements	Parameter that defines the water quality level required for the company's processes.
	Quality satisfaction	Measure that indicates if the ecosystem's water quality complies with the industry's water quality requirements.
	Water with the quality requirements	Volume of water that complies with the quality requirements.
	Water treatment	Volume of water treated to remove pollutants.
Water availability for the company	Volume of water available for the company's processes.	
[46, 63]	Energy consumption	Amount of energy used for the company's processes.
	Energy supply	Amount of energy supplied to the industry.
	Energy security	Measure that indicates if the company's energy supply is reliable or not.
[39, 44, 45, 64]	Fossil fuel energy use	Amount of energy from fossil fuels.
	Emissions to air related to fossil fuel energy use	Emissions of air pollutants produced by the use of fossil fuels.
	Company's emissions to air	Pollutant substances released by the company to the atmosphere.
	Air quality	Measure of the amount of pollutants in the atmosphere that indicates the environmental impact produced to the air.
	Pressure to reduce emissions	Actions taken to promote the reduction of pollutant emissions to air.
Adoption of environmental friendly alternatives	Alternatives that lead to the reduction of emissions of air pollutants.	
[36, 61]	Ecosystem's industries water demand	Volume of water required by the industries and the population in the ecosystem.
	Ecosystem's population water demand	Volume of water required by the population in the ecosystem.
	Ecosystem's industries emissions to water	Volume of wastewater produced by the industries and the population in the ecosystem.
	Ecosystem's population emissions to water	Volume of wastewater produced by the population in the ecosystem.
	Ecosystem's industries energy consumption	Amount of energy required by the industries and the population in the ecosystem.
	Ecosystem's population energy consumption	Amount of energy required by the population in the ecosystem.
	Ecosystem's industries emissions to air	Volume of air pollutants emissions produced by the industries and the population in the ecosystem.
Ecosystem's population air emissions	Volume of air pollutants emissions produced by the population in the ecosystem.	

The global analysis of the causal loop diagram shows that the company's production rate is the key variable that influences the four environmental impact factors, and it also becomes affected by those factors. This means that if at least one of them is out of control, the company and their processes will be seriously affected, and their future will be compromised. Therefore, this research highlights that it is important to strive to maintain and ensure a balance between the consumption of natural resources and the emission of pollutants.

6 Conclusions and Future Work

By using the SD approach and a causal loop diagram, this research proposes a model that analyzes the following aspects: 1) the uncontrolled interactions between a company and the ecosystem, which are produced by four environmental impact factors: water consumption, energy consumption, emission of water pollutants, and emission of air pollutants, and 2) SD is a tool that enable to model in an integrated manner the different interactions between the company and the ecosystem, because it follows an holistic approach, which allows for the analysis of larger spatial and temporal scales.

Likewise, this new model provides the foundations to construct simulation models for sustainability assessment that efficiently provide information to develop strategies that ensure the conservation of the environment. Similarly, the model demonstrates that environmental damages contribute to a difficult regeneration of natural resources, which hence limits the development and correct operation of companies.

As future work, the conceptual model proposed will be applied in a case study by following the stages described in the methodology section, with the aim of validating the model in its field of application and obtaining feedback about it. Finally, the usefulness of this model can be improved by integrating more environmental impact factors, such as the soil use and the generation of solid waste, among others. This will provide a better understanding and a more complete view of the damages that companies cause to the ecosystems.

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