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Social Impacts Assessment of PVC Resin Production Process Via Joint Social Life Cycle Analysis and Theory of Change

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Abstract

This study assesses the social impacts of a suspension polyvinyl chloride (PVC) production plant using a hybrid methodology combining social life cycle analysis and the theory of change, two locations were considered (Colombia and Belgium). The methodology was based on UNEP/SETAC guidelines, using data from corporate and sectoral reports supplemented with data from national and international governmental and non-governmental databases. The theory of change serves as the base for indicator selection. Additionally, a sensibility analysis was conducted to observe how the process performance is affected when performance reference points (PRPs) and the functional unit are varied. The analysis revealed a higher social performance score for the plant located in Belgium; however, both locations showed positive performance. The studied indicators showed that the plants perform above compliance (above 0.5) regarding workers, partly due to current regulations in both countries. However, aspects associated with communities and society showed regular performance due to negative impacts associated with the use of natural resources. Furthermore, a sensibility analysis was conducted by varying performance reference points and the functional unit from 418,000 to 500,000 tons per year. The first analysis showed that when comparing process performance to development goal-based targets, process performance (for the Colombian plant) decreases by 24% but remains close to compliance (0.44). The indicators for local communities are the most affected with a decrease of up to

60%. Additionally, limitations over data availability and consistency were detected. Lastly, an increase in process flow (functional unit) benefits the process's social impact due to an increase in the plant's workforce.

Keywords: Social life cycle assessment; polymers; PVC; green industry; theory of change; sustainability; social responsibility; Stakeholders; Sensibility; Computer-aided process engineering.

Evaluación de Impactos Sociales del Proceso de Producción de Resina de PVC Mediante Análisis de Ciclo de Vida Social y Teoría del Cambio

Resumen

En este estudio se realiza una valoración de los impactos sociales de una planta de producción de policloruro de vinilo o PVC por suspensión usando una metodología híbrida que combina el análisis de ciclo de vida social y la teoría del cambio, considerando dos ubicaciones (Colombia y Bélgica). La metodología se basó en las guías UNEP/SETAC en la cual se utilizó información proveniente de informes corporativos y sectoriales complementada con información de bases de datos de organizaciones gubernamentales y no gubernamentales nacionales e internacionales. La teoría del cambio sirvió como base para seleccionar los indicadores. Además, se realizó un análisis de sensibilidad para observar cómo se ve afectado el desempeño del proceso cuando se varían los puntos de referencia de desempeño (PRD) y la unidad funcional. El análisis reveló una puntuación de desempeño social más alta para la planta localizada en Bélgica, sin embargo, ambas locaciones presentaron un desempeño positivo. Los indicadores estudiados mostraron que las plantas presentan un desempeño por encima de la conformidad (por arriba de 0,5) con respecto a los trabajadores, en parte por la regulación actual. Sin embargo, aspectos asociados a las comunidades y a la sociedad presentan un desempeño regular por impactos asociados al uso de los recursos naturales. Por otro lado, se realizó un análisis de sensibilidad variando los puntos de referencia de desempeño (PRD) y la unidad funcional de 418.000 t/año a 500.000 t/año. El primer análisis indicó que cuando se compara el desempeño del proceso a metas basadas en objetivos de desarrollo sostenible (ODS), el desempeño del proceso (para la planta colombiana) disminuye un 24%, pero se mantiene cerca

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de la conformidad (0,44). Los indicadores para las comunidades locales son los más afectados con una disminución hasta un 60%. Adicionalmente, por último, un aumento del flujo de proceso (unidad funcional) beneficia el desempeño social del proceso debido a un aumento de la fuerza laboral de la planta.

Palabras clave: análisis del ciclo de vida; polímeros; PVC; industria verde; impacto social; sostenibilidad; responsabilidad social; grupos de interés; sensibilidad; ingeniería de procesos asistida por computadora.

1. Introduction

Plastic compounds have become an essential material in the daily life of societies worldwide, such as polyvinyl chloride (PVC), due to their advantageous chemical and mechanical properties (Mijangos, Calafel and Santamaría, 2023). PVC is primarily produced (80% of the supply) using the suspension polymerization method, known for its high productivity and the ability to control polymer properties (Saeki and Emura, 2002). However, the PVC production process by suspension is characterized by a series of negative impacts, such as intensive energy use, mainly from non-renewable sources (93.8%) (Ludmann, Fröhlich and Liebich, 2015), high water consumption (Wang et al., 2019), emission of significant pollutants such as greenhouse gases (GHGs) (Bottausci et al., 2021), wastewater (Tian et al., 2020), and low PVC recycling rates in other stages of its life cycle (Lewandowski and Skórczewska, 2022). These negative impacts have increased not only the demand for more sustainable practices by consumers but also the awareness of companies and policymakers. Since the establishment of the 2030 Agenda and the Sustainable Development Goals (SDGs), the concept of sustainable development has become a priority for organizations dedicated to chemical manufacturing; this concept recognizes three pillars—environment, society, and economy—as equally important (Pollok et al., 2021). For economic organizations, balancing economic production with environmental and social impacts has become a determinant of competitiveness. However, the growing sensibility to climate change and environmental issues has focused the recent discussion among sustainability experts on environmental sustainability, sidelining social sustainability (García-Muiña et al., 2021).

Social aspects are rarely considered, due to limited awareness of their related benefits and, to a lesser extent, limitations in methodologies for their evaluation (Ardolino, Palladini and Arena, 2023). However, the need to assess and understand the social impact of chemical processes at different levels (local and global) is an urgent concern for both researchers and policymakers. Social Life Cycle Assessment (s-LCA) has emerged as a relevant tool for evaluating the social performance of chemical processes (Traverso, 2018), as it provides a systematic framework for assessing the (potential and/or actual) social impacts of products and services throughout their life cycle using quantitative and qualitative data (United Nations Environment Programme, 2020). Unlike environmental life cycle assessment, the definition of stakeholders forms the basis of an s-LCA evaluation as they are the ones receiving the impacts, both positive and negative. Social impacts are classified according to stakeholder categories, and from these arise impact subcategories comprising socially significant issues or attributes (Andrews et al., 2013). These subcategories are assessed using impact indicators, which are directly related to the product life cycle inventory. For the assessment of the social performance of a product or service, two approaches are used: a Type I approach based on performance reference values and a Type II approach based on the causal relationship between impacts and the product system (Baraibar-Diez, Llorente and Odriozola, 2023). The information provided by s-LCA serves decision-making and promotes dialogue among stakeholders with the aim of improving an organization's social performance and, ultimately, the well-being of stakeholders (Takeda et al., 2019). This method provides information on social and socio-economic aspects for decision-making, fostering dialogue on social and socio-economic aspects of production and consumption, with the aim of improving organizational performance and, ultimately, stakeholder well-being (Fürtner et al., 2021). However, s-LCA is still in an early stage of development, lacks methodological consistency and standardization, along with the difficulty of quantifying social impacts and lack of accessibility to data, are

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some of the issues with this methodology (Ertz et al., 2023). The main guidelines have been developed by UNEP (United Nations Environment Programme) where s-LCA complements environmental life cycle assessment by sharing its methodological framework (ISO 14040) but focusing on the impact of processes or products on one or several stakeholder groups (Kokare, Oliveira and Godina, 2023).

Theory of Change is a method that explains how a given intervention, or a set of interventions, is expected to lead to a specific change in development, based on a causal analysis grounded in available evidence (United Nations Development Group, 2015). A Theory of Change can be developed for any level of intervention, whether it is an event, a project, a program, a policy, a strategy, or for an organization (Pacheco and Archila, 2020). The causal analysis is based on methodologies such as outcome chains or logic frameworks (logframes), in which a series of activities, short and long-term results, and impacts are identified (Rogers, 2014). Various United Nations agencies such as the United Nations Development Programme (UNDP) have designed guidelines for developing Theories of Change for the creation of programs that produce socio-economic changes at all levels of society.

In the literature, there has been an increasing number of studies utilizing s-LCA to assess social performance. Studies analyze a wide range of products and processes with varying scopes, such as bioproducts like the sugar cane industry (Prasara-A and Gheewala, 2018), brine treatment processes (Tsalidis et al., 2020), desalination plants, recovery of packaging waste (Yıldız-Geyhan, Altun-Çiftçioğlu and Kadırgan, 2017), rubber production (Dunuwila et al., 2022), and fertilizer production (Martínez-Blanco et al., 2014), as well as energy and textile sectors (Senthilkannan Muthu, 2019), and wastewater recovery processes from electronics and semiconductor production (Serreli et al., 2021), among others. Regarding research on plastic materials, some studies stand out, such as Papo and Corona's study applying a combined life cycle assessment (social, economic, and environmental) to assess the sustainability of high-density polyethylene bottles with a circular economy focus (from cradle to grave) and comparing between virgin and recycled bottles (Papo and Corona, 2022). Ardolino et al. assessed the social impacts of plastic waste management schemes (door-to-door) at the European level using a combination of social and environmental life cycle assessments (Ardolino, Palladini and Arena, 2023). Dobon-Lopez et al. employed a combined life cycle analysis to assess the sustainability of the European plastics industry, including social analysis; a cradle-to-gate approach was used (Dobon Lopez et al., 2009).

On the other hand, there are significant research efforts focused on analyzing the sustainability impacts of the PVC production chain. In the case of using life cycle assessment (LCA), these efforts mainly concentrate on studying environmental impacts (E-LCA), modifying considerations or approaches such as the scope of analysis (for example, from cradle to grave, from cradle to gate, from gate to grave, etc.) (ISOPA, 2012; Comanita et al., 2016; Franklin Associates, 2020; Turner and Filella, 2021; Ramboll, 2022). According to the authors, there is currently no life cycle assessment combined with theory of change specifically aimed at quantifying exclusively the social impacts of the PVC value chain or any of its stages; therefore, this work will be the first of its kind. For the aforementioned reason, this study aims to evaluate the social impacts of the PVC production process by suspension using social life cycle assessment (SLCA), considering an organizational approach for a plant located in Belgium (European Union) and Colombia. This analysis utilizes theory of change to establish the most relevant indicators based on recent trends in desired objectives by productive organizations at regional, national, and international levels. Additionally, a sensibility analysis is conducted to study how changes in different variables affect social impacts. Furthermore, it aims to establish a meaningful benchmark for the socio-economic performance of the process and identify possible improvement strategies.

2. Methodology

In Figure 1, the methodology used in this work to assess the social impacts of the PVC production process by suspension on an industrial scale is illustrated. This methodology was based on the one developed by Gonzalez-Delgado et al., for assessing the social impacts

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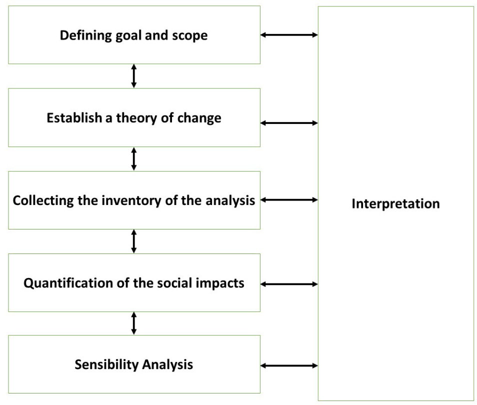
of a shrimp biorefinery using social life cycle assessment (s-LCA) within a framework of theory of change, along with sensibility analysis (González-Delgado, Moreno-Sader and Martínez-Consuegra, 2022). The s-LCA follows the UNEP/SETAC guidelines for assessing the social life cycle of products, using the ISO 14044 standard, which consists of four phases or stages. The first phase involves defining objectives and scope, where the process (or product) is described, analysis objectives, the functional unit, and system boundaries are selected and detailed. The inventory collection phase involves collecting and organizing process information, whether quantitative, semi-quantitative, or qualitative data. The impact assessment phase characterizes and quantifies the impacts according to stakeholder groups or through a global indicator. Finally, the interpretation phase analyzes the results, and conclusions and recommendations are established (Wu, Yang and Chen, 2014). To these stages, the theory of change was added as a method to identify relevant categories and indicators, emphasizing the vision for the process and the sector in the future. This is based on a review of different plans or programs for the sector in the countries studied, such as institutional or organizational objectives or targets (Shahrzad, Schluep and Van den Brink, 2019). In the sensibility analysis stage, the effects of changes in variables on the social performance of the process are studied. For this purpose, the analysis of the process flow (functional unit) effect on the performance of indicators and overall social performance was proposed. Additionally, different scenarios were proposed for selected reference values and how these influence the process performance.

Figure 1. Methodology for assessing the social impacts of an industrial process with a theory of change approach.



Goal and scope

The objective of the analysis is to assess the social impacts of a suspension PVC production plant, identify critical points where the process negatively impacts, and find opportunities that lead to recommendations to improve the sustainable performance of the process in social matters. In Figure 2, the geographical boundaries of the analysis are depicted, with two different locations selected: Antwerp, Belgium, part of the European Union, and Cartagena, Colombia. Choosing two locations facilitates decision-making by comparing the social performance of the process, taking into account the "context" of each location. This "context" includes aspects such as the regulatory framework of each country, corporate responsibility regarding social impacts, industrial development policies, among others (Osorio-Tejada et al., 2022). On the other hand, the representative information used for this analysis comes from various sources such as databases, corporate reports, reports from government organizations, etc. Finally, a temporal framework between the years 2021-2023 was specified.

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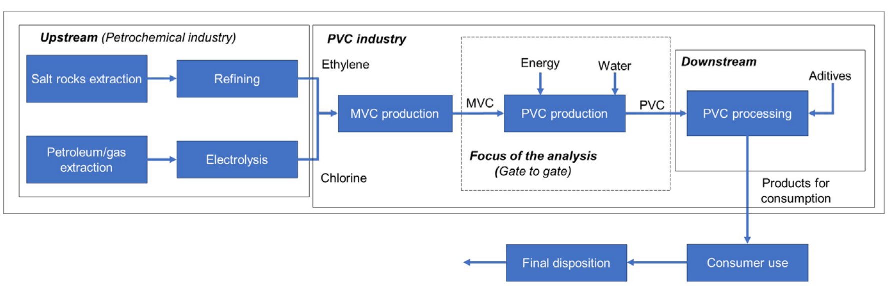
Figure 2. Selected locations for the social impacts analysis of a PVC production process.

In Figure 3, the established boundaries for the study system within the PVC value chain are depicted. The production process under study transforms vinyl chloride monomer formed from compounds produced in upstream stages (ethylene and chlorine) into Poly(vinyl Chloride) resin, which is then processed in downstream stages into consumer products such as pipes, cables, etc. The functional unit (FU) for this social life cycle assessment was established as the annual production capacity of the process, which is 420,000 tons per year of PVC resin (rigid, without plasticizers or additives).

Figure 3. *Stages of the life cycle of the PVC at industrial scale.*



For the system boundaries studied in this work, a gate-to-gate approach was selected, in which only the impacts of the manufacturing stage of the product under study (PVC resin) are considered. In this case, only the suspension PVC production plant (an intermediate product within the PVC value chain) was considered along with the stages or process units comprising the plant. On the other hand, certain stages of the chain such as the transportation of materials like reagents and products were not analyzed. It was assumed that the studied plant is not responsible for transporting substances, a decision made considering that PVC resin-producing companies commonly do not directly handle substance transportation, but rather rely on suppliers and consumers. Additionally, not considering transportation helps simplify data collection for the inventory.

In Figure 4, the PVC production process by suspension on an industrial scale is observed. The process consists of 4 sections: a reaction section, a residual monomer recovery section, a monomer purification section, and a polymer drying section. In the polymerization section, the polymerization reaction occurs. In this stage, the polymer is produced within a suspension of the monomer with water, an initiator, and a stabilizer in constant agitation at a constant temperature. This reaction is exothermic and has a conversion rate of around 85%. The operation is carried out in several reactors in parallel at a temperature of 70 °C and a pressure of 10 kg-f×cm^{-2}. A liquid MVC stream contains fresh monomer and recirculated monomer in a ratio of 80:20 along with demineralized water, 20% dissolved polyvinyl alcohol, and a 20% dissolved initiator, both by weight at 10 kg-f×cm^{-2} and 32°C (Aguilar-Vasquez, Ramos-olmos and González-Delgado, 2023). At the end of the reaction, a heterogeneous mixture remains containing solid polymer, unreacted monomer, water, initiator, and stabilizer.

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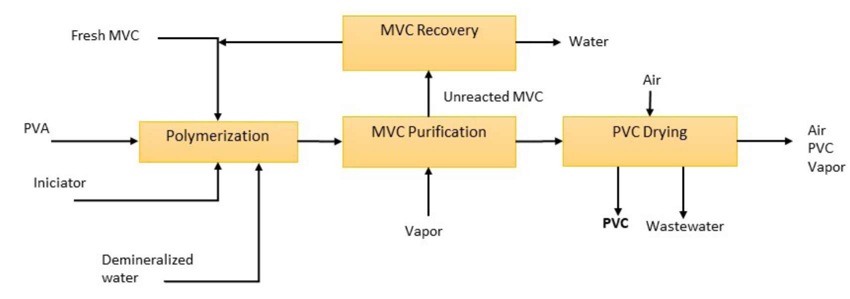
Figure 4. *Process flow diagram of a PVC production by suspension on an industrial scale.*



In the MVC purification section, excess residual monomer is removed from the slurry following international regulations (the MVC content in the polymer must not exceed 1 ppm) (Ministerio Español de Medio Ambiente, 2002). For MVC removal, a gasification stage is employed where the pressure is reduced to 1.8 kg-f×cm^{-2}. This pressure change allows for the unreacted monomer's volatility to separate it from the liquid phase of the suspension (around 95%). Subsequently, the remaining fraction of the monomer (5%) is removed in a stripping column (absorption) using a high-pressure and temperature steam stream (14 kg-f×cm^{-2},225°C). As a result, a monomer-rich overhead stream and a bottom stream with less than 1 ppm of the monomer are formed. The monomer-rich overhead stream enters the residual monomer recovery section, which consists of a series of compressors and heat exchangers that condition the residual MVC for recirculation (removal of water and conversion of the monomer to a liquid state). Then, the gas streams exiting the condenser and the gasification stage enter a compressor to be conditioned close to the saturation pressure of the monomer for easy condensation through a heat exchanger and recirculation to the process. The bottom stream from the stripper containing the monomer is mostly water (approximately 70%) that needs to be removed. The suspension enters the water removal section, initially passing through a centrifuge spinning at 1,800 rpm, where about 75% of the water (along with almost all of the PVA and the initiator) is removed from the slurry. The product stream exiting the centrifuge is in the form of wet paste, which is dried in a rotary dryer using hot air, reaching a temperature of 70°C after mixing streams. The resulting polymer moisture content upon exiting the dryer is 0.01% by weight. The stream exiting the dryer is a mixture of air, steam, and polymer entrained particles. The dry polymer is separated in a cyclone, operating at atmospheric pressure (1.03 kg-f×cm^{-2}). The overhead stream consists of air and water vapor along with polymer fractions (0.2% of the total produced), while the bottom stream is the dry granulated polymer with 0.01% water.

Theory of change

To carry out a Theory of Change for this work, the recommendations proposed by Belcher et al. are employed to comprehensively and illustratively describe how to achieve a sustainable PVC industry (Belcher, Davel and Claus, 2020). These recommendations start by defining the overall purpose and then iteratively developing a model of the main activities, products, actors, outcomes, and impacts. Reports and documents from industry organizations serve as the basis for this phase, illustrating the current context of the sector, the goals set, established strategies, and possible effects or impacts of these. With this information available, the desired objective or impact for the process is determined. Based on the strategies, it is possible to establish the activities along with the inputs they need to achieve the objective. Immediately, the short-term (products), medium-term (effects), and long-term (impacts) consequences are considered, as well as possible risks that may hinder them (Cassetti and Paredes-carbonell, 2020). From the above information, a theory is constructed graphically through a diagram detailing the planned route sequentially from activities to the desired impact. Finally, the way to monitor the theory and how it has contributed to change is proposed through measurable indicators that allow feedback to the process (iteration) and decision-making (Dale, Frost and Ison, 2023).

s-LCA Inventory

In the information gathering phase for the inventory, a combination of different types of sources was used. For primary sources, specific process information (at the organizational level)

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was selected, while for secondary sources (or in cases where specific primary information was not available), generic information related to sector and/or national level data was used. Primary information was collected directly from corporate-level information documented in Corporate Social Responsibility (CSR) reports of companies, which serve as an important source of information on organizational performance (Nechaev and Hain, 2023). Secondary information was compiled from documents and databases of international organizations such as the International Labour Organization, World Bank, Organisation for Economic Co-operation and Development (OECD), etc. Additionally, national-level organizations such as ministries or government agencies like Eurostat, and sector-specific reports or initiatives from industry associations like PlasticsEurope/VinylPlus in Europe, and Acoplásticos in Colombia, among other organizations, were utilized.

Table 1 lists the different categories and subcategories suggested by the guidelines for the s-LCA. The selection of these categories and subcategories is conditioned by considerations established during the objective and scope phase, such as the functional unit, the system (including geographical location) under study, and the most relevant stakeholders, among others.

Table 1. *Categories and subcategories of stakeholders suggested by UNEP for s-LCA.*

Stakeholder Categories	Subcategories
Workers	Freedom of association and collective bargaining Child labour Fair salary Working hours Forced labour Equal opportunities/discrimination Health and safety Social benefits/social security
Consumers	Health and safety Feedback mechanism Consumer privacy Transparency End of life responsibility
Local community	Access to material resources Access to immaterial resources Delocalization and migration Cultural heritage Safe and healthy living conditions Respect of indigenous rights Community engagement Local employment Secure living conditions
Society	Public commitments to sustainability issues Contribution to economic development Prevention and mitigation of armed conflicts Technology development Corruption
Value chain actors (not including consumers)	Fair competition Promoting social responsibility Supplier relationships Respect to intellectual property rights

Additionally, the theory of change allows for the identification of subcategories based on the needs of the process or sector, through the identification of objectives that must be monitored using indicators. The indicators serve as a direct measure of the social

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performance of the process, and for their selection, it is necessary to conduct a literature review to find the suitable parameters or variables for the studied system (in this case, the industrial process of PVC by suspension). For this work, the Global Reporting Initiative (GRI) indicators served as the basis for the search for indicators, as these are used in corporate social responsibility reports. Additionally, there are no limitations on using quantitative, semi-quantitative, or qualitative data; the choice depends on the nature of the indicator and the availability of information.

Social impact assessment

Impact Assessment can be conducted using the benchmarking method (Type I). For this work, Type I will be employed, in which Performance Reference Points (PRPs) are utilized. These PRPs are established for each social subcategory (and its respective indicator or indicators), considering international standards, best practices from the sectors under analysis, or other factors strictly related to the context and nature of the study. To calculate the performance of the indicators, the Performance Reference Points (PRPs) are normalized on a scale from 0 to 1, where 0 represents the lowest social performance and 1 represents the best social performance. Since it is assumed that the final values of the indicators represent positive social performance, the normalization procedure for indicators with different improvement directions varies. For quantitative indicators, the range between the minimum and maximum reference values is used to normalize the quantitative indicator:

For an indicator in which the desired direction of improvement is positive (where 1 represents the best social performance and 0 represents the worst social performance), the normalization procedure is as follows:

$$Performance = \frac{x_i - x_{min}}{x_{max} - x_{min}} * 100\% \quad (1)$$

For an indicator in which the desired direction of improvement is negative (where 0 represents the best social performance and

1 represents the worst social performance), the normalization procedure is as follows:

$$Performance = \frac{x_{max} - x_i}{x_{max} - x_{min}} * 100\% \quad (2)$$

Where is the analyzed indicator, and are the minimum and maximum performance reference points for each indicator under study. On the other hand, for qualitative indicators, similar to quantitative indicators, a scale of 0 and 1 is used to assess performance, but a mathematical expression like normalization is not used. Instead, a yes/no question is employed, where yes represents the highest social performance and no represents the lowest social performance.

On the other hand, to establish an overall social performance score for a product and/or service, the technique of aggregation using weighting factors for indicators or subcategories is employed. This allows combining and summarizing multidimensional information into a single index in order to better communicate and understand the results obtained. The weighting factors used for this analysis are based on those assumed by González-Delgado and colleagues in their social analysis work for a shrimp biorefinery (González-Delgado, Moreno-Sader and Martínez-Consuegra, 2022).

Results interpretation

In this phase of the analysis, the findings from previous stages are interpreted according to the defined objectives and scope in order to establish conclusions and recommendations, along with identifying the major contributors to social impacts and proposing changes to improve these impacts based on the results of the impact assessment stage. Additionally, emphasis is placed on identifying significant problems and critical social points of the system. In situations of uncertainty, tests such as data quality analysis through sensibility analysis or uncertainty analysis can be applied. Furthermore, additional recommendations can be made for the study audience. To describe the performance of the indicators, subcategories, or the entire process, the classification established in Table 2 is employed, where the level of conformity with respect to the social performance reference points is shown, primarily the goal of each one. If the process has a score of 1, its performance is ideal compared to the PRPs; conversely, a score of 0 indicates non-conformity, while a value of 0.5 indicates conformity with the PRPs. Scores between 0.5 and 0.75 indicate above-conformity, while scores between 0.25 and 0.5 indicate non-conformity but with improvement shown (Bonilla-Alicea and Fu, 2021).

Table 2. *Level of compliance according to the value of the studied indicator.*

Value	Compliance level
1	Ideal performance
0,75	Progress beyond compliance
0,5	Compliance with PRP*
0,25	Non-compliant with PRP but improving
0	Non-compliant and no signs of improving

**PRP: performance reference points.*

Sensibility analysis

For this final phase, the study considers the effect of changing the subcategories (indicators) on the social performance of the process. In this study, the methodology follows a consideration: for each proposed case or scenario, only one variable change while the others remain constant. Unlike environmental parameters, the nature of social indicators requires selecting from the studied subcategories those that have a more direct relationship with the modified variables. For this purpose, scenarios are proposed where the functional unit and the reference values selected in the inventory phase will be modified. In the case of the functional unit, it represents the production capacity of the plant, which should increase as indicators such as hiring new personnel increase, as there is a direct relationship between both parameters. On the other hand, changing the reference values conditions the performance of the indicators. For example, there are indicators based on goals associated with sustainable development objectives. Many companies in the plastics sector derive their goals from the SDGs, and this study will assess where the process stands if performance is evaluated against these objectives.

4. Results and Discussion

Theory of change for PVC production

The subcategories and performance indicators for each stakeholder were selected according to the expected results. To do this, a theory of change framework was constructed to achieve the goals desired by representative organizations of the PVC sectors such as Acoplásticos in Colombia and VinylPlus in Belgium. Based on these established institutional objectives, the most representative subcategories from the UNEP/SETAC guidelines were selected. Figure 5 shows a schematic representation of the theory of change approach derived from sectoral and corporate reports of organizations within the PVC value chain. It is worth noting that the European PVC industry leads in terms of sector improvement policies; they have established goals and voluntary strategies focused on sustainability criteria, based on science and risk (VinylPlus, 2023). In the case of Colombia, it has used the European plastics sector as a basis for establishing new sectoral policies, aiming to establish a circular economy as the foundation for a competitive industry (Colombia Productiva, 2019).

For the PVC industry, an industry with a circular economy focus, low environmental impacts, and commitment to social welfare has been identified as a desired goal. This goal encompasses technical, economic, and social aspects. Sector organizations emphasize the technical aspect, focusing on increasing technological capabilities to address sustainability issues in the PVC value chain. Technological

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development (research, development, and innovation, R&D) is expected to serve as a key activity for implementing a production system based on circular economics by revaluing substances and keeping them within the PVC chain. This development involves allocating resources and research activity within companies to generate reliable technologies that maximize benefits (Hassani, Silva and Al Kaabi, 2017). One of the main research focuses is to improve the PVC process's ability to process recycled material from other stages of the life cycle through chemical treatments (Lewandowski and Skórczewska, 2022), while also advancing methods for collecting and segregating plastic waste (Miliute-Plepiene, Fråne and Almasi, 2021). Additionally, the creation of new technologies is expected to enable the manufacturing of new products based on green chemistry, such as organic-based polymers with lower environmental footprints and greater natural degradation (Spierling et al., 2018), along with the use of less polluting substances (such as additives, catalysts, and pigments). Furthermore, Industry 4.0 and digitization will play an important role in process operation by managing real-time data, allowing for the identification, monitoring, and resolution of problems to maintain productivity at maximum levels through automation (predictive) (Biron, 2020).

On the other hand, the adaptation of new production practices is recognized as another set of relevant activities to achieve a more sustainable value chain. These practices involve strategies based on criteria ranging from technical-environmental to socio-economic aspects. Achieving carbon neutrality has been identified as one of the most significant objectives for PVC producers. The implementation of Renewable Energy Technologies (RET), such as the use of renewable energies (solar or wind), the use of alternative fuels such as hydrogen or energy carriers from biomass, and including carbon capture technologies, allows for the reduction of greenhouse gas emissions. However, some of these technologies are limited in their technological maturity (technology readiness level) (Semeijn, 2021), and it is expected that technological development will advance the implementation of these technologies by accelerating their commercialization (lower cost). On the other hand, there is a search for establishing systems that improve the ecological footprint while seeking to reduce costs in the value chain processes. For this, sector organizations propose to increase process efficiency through efficient resource stewardship, maximizing the use of substances serving as inputs such as water, reagents, and industrial services, while reducing their consumption. Optimization through process integration methodologies allows for identifying opportunities to maximize the use of streams (intermediates) (Moreno-Sader, Martínez-Consuegra and González-Delgado, 2021), as well as reducing waste emissions through reuse and regeneration (Lindqvist, 2011; Prieto et al., 2016).

Additionally, there is a push to adopt new strategies for process safety improvement, prioritizing the implementation of preventive measures to mitigate risks. On the other hand, establishing verification and monitoring systems for emissions through the creation of extended responsibility systems, using a life cycle approach (LCA) to characterize and identify the flows of chemical substances generated by the process. Furthermore, strengthening the human base within organizations through training criteria and working conditions serves as a way to improve people's quality of life. It is intended that these production changes will enable the development of more environmentally friendly products and bring greater economic benefits to organizations by substantially reducing costs. Similarly, it is hoped that these new practices will serve as a basis for establishing new operational standards, which will eventually evolve from voluntary commitments into more updated laws and regulations.

On the other hand, it is identified as a priority for the sector to enhance interaction with various stakeholders, whether they are direct participants in the chain (raw material producers, consumer product manufacturers, and workers), as well as for indirect ones (communities and consumers) (Everard, 2020). This collaboration among stakeholders focuses on jointly adopting clean production criteria, as well as participating in identifying challenges, opportunities, and devising strategies to address them. Likewise, better cooperation with different actors facilitates citizen participation and knowledge transfer scenarios. This exchange fosters the creation of new business opportunities (economic investment and business creation) because the needs to maintain

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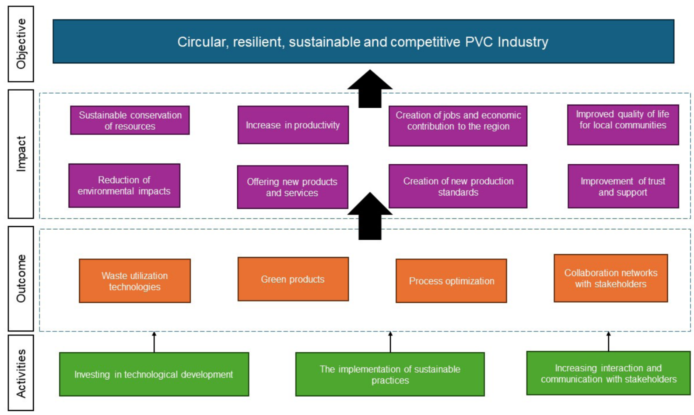
a circular economy (infrastructure, operation, etc.) require a substantial increase in both direct and indirect workers (Hestin, Faninger and Milios, 2015); furthermore, it raises awareness among consumers and society about the benefits of an industry committed to sustainable development (Del-Aguila-Arcentales, Alvarez-Risco and Yáñez, 2023), aiming to increase demand for sustainable products and support policies that accelerate the achievement of such industry.

Figure 5. *Scheme of the theory of change for the PVC production industry.*



For the s-LCA of the suspension PVC production plant, four stakeholder groups were selected according to the boundaries considered and the categories suggested in the UNEP/SETAC guidelines (United Nations Environment Programme, 2020). Stakeholders selected include workers, individuals involved in the processing production lines; the local community, people living in areas surrounding the plant; society, representing individuals who interact indirectly with the plant, and other actors in the value chain. Consumers were not selected because a PVC resin manufacturing plant does not directly interact with any end consumer in the chain; the only "consumers" are other companies in the value chain, such as plants that convert resin into consumer products like pipes.

Table 3 shows the selected indicators for the environmental assessment of the suspension PVC process. These summarize the subcategories chosen for each category of direct actors, with which the expected social changes are measured when this intervention is carried out in both scenarios. The selected subcategories arose from the theory of change conducted, and the selected indicators were chosen based on the literature. At least one indicator was considered for each subcategory, with the exception of the social benefits/social security subcategory, which presented two indicators; a single representative indicator was not identified. Additionally, the information used for the indicator was displayed, prioritizing specific organizational-level data (org). However, for indicators related to norms or regulations such as labor laws, a combination of country-level (country) and sector-level (sector) data was used. The majority of the PRPs for each indicator also resulted from this combination of organizational, sectoral, and national data. Furthermore, the desired direction for each indicator was identified, whether it should be maximized or minimized. For quantitative indicators (quant), equations (1) and (2) were used, and for qualitative indicators (quali), a yes or no approach was applied.

Table 3. *Selected indicators for the S-LCA of a suspension PVC production plant.*

Stakeholders' category	Subcategory	Unit	Indicator	Type	Desired goal	Type of PRP	Reference
Workers	Health and safety	Work accident rate	TRIR+	Quant	Min	Org	(Siebert et al., 2018)
	Fair salary	Relation between decent wage and the median wage of the sector	%	Quant	Max	Sect/ country	(Martínez-Blanco et al., 2014)
	Working hours	Working hours	h	Quant	Min	País	(Traverso et al., 2021)
	Freedom of association and collective bargaining	Fraction of unionized workers	%	Quant	Max	Org/sect	(Traverso et al., 2021)
	Equal opportunities/ discrimination	Gender proportion	%	Quant	Max	Org	(Traverso et al., 2021), (Reinales, Zambrana-Vasquez and Saez-De-Guinoa, 2020)
	Social benefits/social security	Number of vacations date	Days	Quant	Max	Country	(García Sánchez, Padilla-Rivera and Güereca, 2023)
		Training and education	h	Quant	Max	Org/ country	(Traverso et al., 2021), (Reinales, Zambrana-Vasquez and Saez-De-Guinoa, 2020)

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***Table 3.** Selected indicators for the S-LCA of a suspension PVC production plant.*

Stakeholders' category	Subcategory	Unit	Indicator	Type	Desired goal	Type of PRP	Reference
Local community	Local employment	Hire rate	%	Quant	Max	Org/sect	(Traverso et al., 2021)
	Community engagement	Investment with direct benefits to the community	$	Quant	Max	Org	(Cadena et al., 2019)
	Safe and healthy living conditions	National multidimensional poverty	%	Quant	Min	País	(Traverso et al., 2021)
		Reused waste	tCO2/t	Quant	Min	Org	(Traverso et al., 2021)
	Secure living condition	Intensive water use	m3/t	Quant	Min	Org	(Traverso et al., 2021)
	Access to material resources	CO2 emissions scope 1	%	Quant	Max	Org	(Traverso et al., 2021)
Value chain actors (excluding consumers)	Supplier relationships	Local suppliers	%	Quant	Max	Org	(Cadena et al., 2019)
	Promoting social responsibility	Supplier monitoring programs*	Y/N	Quali	Yes	Org/sect	(Traverso et al., 2021)
Society	Technology development	R&D investment	$	Quant	Max	Org/ country	(Traverso et al., 2021)
	Contribution to economic development	Participation on the national GDP	$	Quant	Max	Org/ country	(Traverso et al., 2021)
	Public commitments to sustainability issues	Energy intensity	MWh/t	Quant	Min	Org	(Traverso et al., 2021)

*% = percentage; $ = dollars; Y/N = yes or no; Quant = quantitative; Quali = qualitative; *two options = if you have a supplier monitoring program (1) and do not have a supplier monitoring program (0); +(Number of recordable incidents by OSHA) X 200,000 / (Total number of hours worked)*

Analysis of social performance of PVC production process

In Figure 6, the performance of the evaluated indicators for the industrial-scale PVC production process by suspension method is observed. Regarding indicators associated with workers, both plants demonstrate acceptable performance with scores in conformity or progress above conformity according to the PRPs. The indicator of working hours has the best performance with a score of 1 for Belgium, while for Colombia, it is 0.75. In the European case, the adoption of 40-hour workweeks (even 38-hour workweeks) has benefited industrial plant workers (Federal Public Service, 2024). In Colombia, this change has occurred slowly, with legal working hours set at 42 hours. The rate of occupational accidents shows that both plants have good performance (0.85 for both). There is an emphasis on the application of safe work strategies at both locations. Occupational safety in the chemical industry is a sensitive issue in both countries, so organizations are committed to actively identifying and mitigating any risks resulting in accidents (Riaño, M., Hoyos, E., Valero, 2016). Personnel training within the plants has a score of 0.72 for Belgium and 0.54 for Colombia. Both countries benefit from laws seeking to compel employers to continuously improve the workforce in the sector (Article 21 of Law 50 of 1990). The difference between the two countries is an average of one hour less per year, which positively impacts the workers of both plants, but Belgium's plant benefits more. The number of vacation days is in conformity with what is found in the sector; for both plants, vacation time meets the minimum required by law or is slightly above. However, the context of both countries changes radically when considering aspects such as special regimes, labor agreements, and even the number of holidays per country, with Colombia having more holidays than Belgium. The ratio between the average sector salary and the living wage showed that both countries adequately remunerate their workers. Compensation laws reduce the risk of inadequate compensation. Additionally, the use of skilled and specialized labor necessitates competitive salaries to attract personnel. The gender ratio was the indicator with the worst performance for both locations. The chemical industry faces the problem of lack of gender equality when hiring female personnel, with both plants falling below figures found in the sector. On the other hand, Colombia benefits from social programs aimed at the labor integration of women in various sectors, including the industrial sector (Quintero, 2023).

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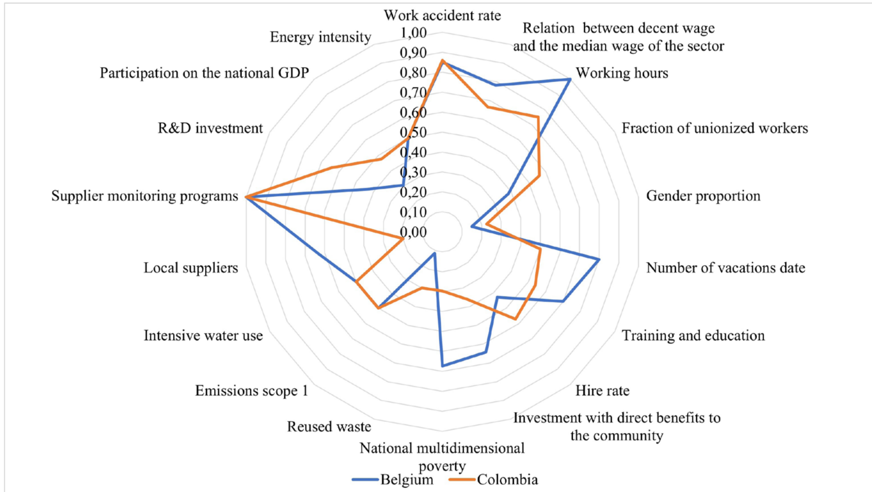
***Figure 6.** Social performance of the selected indicators of a suspension PVC production plant.*



In the indicators associated with the local community, the Figure shows that most indicators are in conformity, with one indicator in non-conformity but improving with respect to the PRPs. The employment creation potential for both plants is at least in conformity (at least 0.5 for both). Surprisingly, Colombia demonstrates a higher performance (0.57) than Belgium. The plant in Colombia exhibits a high employment creation potential compared to other companies in the petrochemical sector, resulting in positive effects by increasing job opportunities in the communities, especially for individuals with higher education levels (Carranza, Wiseman and Eberhard-Ruiz Ana Lucía Cárdenas, 2021). In the case of Belgium, the plant shows a lower employment creation potential compared to the European PVC sector. This is due to factors such as competition among companies in the sector for the recruitment of skilled personnel, along with a limited supply of qualified personnel, among other reasons (BUSINESS EUROPE, 2023).

Regarding multidimensional poverty, Colombia's performance falls below conformity. National multidimensional poverty in Colombia is comparable to other countries in the continent. Conversely, Belgium exceeds conformity; this country ranks among the countries with the lowest poverty levels globally. For the indicator of direct investment in communities, the plant located in Belgium performs above conformity, while the plant in Colombia is non-conforming but improving. European companies are known for their strong social responsibility (Schmidpeter and Idowu, 2015), illustrated by their investment in community welfare. Colombian companies, on the other hand, are adapting the European approach by promoting investment in surrounding communities. The indicators of CO_2 emissions and intensive water use were in conformity with values recorded in the chemical industry of both countries (0.5 for both locations). For the indicator of substance reuse, it was found that the plant in Colombia performs better (0.30) than the one located in Belgium (0.11). The Colombian plant has a non-conforming but improving indicator; severe annual climate changes (El Niño and La Niña phenomena) make resource availability a critical variable (Linares-Rodríguez, Gambetta and García-Benau, 2023). Competition with communities and ecosystems forces organizations to increase their capacity to minimize resource consumption. The indicators associated with other actors in the value chain show that the plant in Colombia demonstrates non-conformity (0.11) by relying on suppliers located outside the country, unlike the plant in Belgium, which benefits from high industrialization in Europe by having much closer suppliers (0.8). On the other hand, both plants have evaluation and monitoring programs for their local or non-local suppliers, which allow verifying that the companies in the chain comply with the legal regulations associated with sustainability (ideal performance of 1). These programs are based on evaluation systems and labeling of the impacts made by a sectoral organization.

For indicators associated with impacts on society, it was found that the plant in Colombia demonstrates greater conformity compared to the one in Belgium. The indicator of the sector's contribution to the national GDP is in conformity (0.64), while the indicator is in non-conformity but improving (0.48); the plant in Colombia benefits from the country's growing industrialization, allowing GDP contributions to be more significant (Cely-Niño, 2017). Likewise, the growth of industrialization causes different companies in the sector to increase their investment in technological development in pursuit of greater competitiveness and productivity (Maldonado-Pinto and Portilla-Barco, 2020). For the plant in Belgium, the opposite occurs; this plant has a higher

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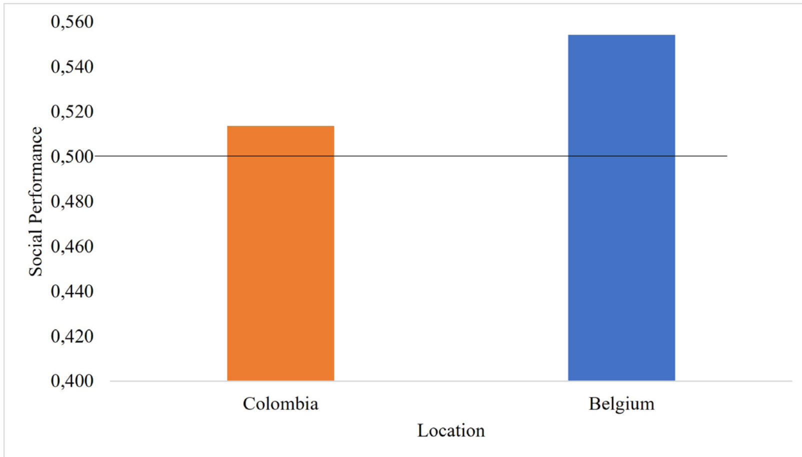
GDP contribution and a greater investment in R&D than Colombia (National Bank of Belgium, 2021). In the European context of high industrialization and productivity, this results in indicators being in non-conformity but improving (0.43 and 0.3, respectively). European plastic sector plants are lagging behind compared to other sectors, as observed in the European commission documentation regarding investment in R&D (European Commission, 2023). On the other hand, the intensive energy use of both plants is in conformity with the sector (plastic/petrochemical) in both countries (0.5 for both locations); neither demonstrates performance above the data of other companies, even globally.

In Figure 7, the overall social performance for PVC production plants located in Colombia and Belgium is shown. Both plants demonstrate social performance in conformity with performance benchmarks, with a score slightly above 0.5, indicating that the suspension PVC production process has an overall positive impact. The plant in Belgium exhibits better social performance than the plant located in Colombia. This is expected because a plant in Belgium not only has better industrial conditions (infrastructure, investment, technological innovation, logistics chains, and public policies, among others) than those found in Colombia but also belonging to the European common bloc allows benefiting from more rigorous organizational standards and development policies that foster better social impacts on the studied stakeholders (Beghetto et al., 2023). However, despite Colombia having a less developed chemical industry, outdated regulation, and a lack of a robust industrial culture, the plant is not far behind from the European plant. The petrochemical sector to which the PVC production plant belongs has identified and accelerated the implementation of new industrial strategies based on SDGs accompanied by drastic changes in regulation focused on corporate responsibility, which have driven improvements in organizations regarding their social impacts (Angel, 2022).

***Figure 7.** Overall social performance of a suspension PVC production plant in Colombia and Belgium.*



In the comparison conducted in Figure 7, it is pertinent to mention that both plants have room for improvement (especially the plant in Colombia) if aiming to achieve performance close to the ideal, considering the current conditions of the sector in the locations studied. On the other hand, the observed performance is based on current sector indicators, which assess the plant within what is expected for PVC suspension plants or plants in the plastics or petrochemical sector. If evaluating the process with respect to an ideal behavior, new target PRPs must be established to assess the social impact of the process. This scenario is necessary considering current sector trends such as the adoption of the circular economy, environmental sustainability, and social responsibility, among others. These scenarios can be analyzed through a sensibility analysis in which the social impact of the process using these new PRPs is quantified and compared to the assessment using sector information.

Sensibility analysis

In Figure 8, the Comparison of social performance when using PRPs based on goals derived from the SDGs (pessimistic scenario) and PRPs based on current sector information (optimistic scenario) is shown. It can be observed that the social performance of the indicators considered shows a significant variation, with a negative trend (decrease), with the exception of several indicators showing

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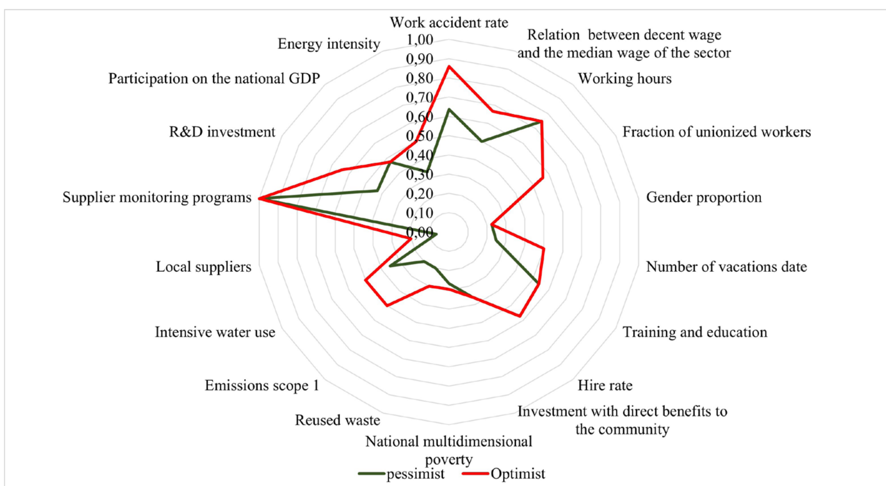
little or no variation. For the workers' subcategory, the accident rate, the ratio between the average sector salary and the living wage, and the number of vacation days decreased between 25% and 50%, leading the last two from the point of conformity to the point of non-conformity, while the remaining indicators did not record any changes. For the community subcategory, 4 out of 6 indicators decreased, making it the category most impacted by the change in PRPs, with a variation towards non-conformity between 10% and 50%. The most affected were the indicators associated with technical aspects such as CO_2 emissions, water consumption, and material reuse, while more social aspects such as employment creation potential and community investment showed no variation between both scenarios; there is no specific goal that organizations must achieve. From the subcategory for other actors in the value chain, the indicator of local suppliers showed a marked decrease with a reduction of 67% compared to the positive scenario, placing it in non-conformity (below 0.25) compared to the optimistic scenario. Finally, the indicators of investment in R&D and energy intensity shifted from conformity to non-conformity with a performance decrease of 33% and 34%, respectively.

Figure 8. *Social performance of the selected indicators of a suspension PVC production plant under optimistic and pessimistic scenarios.*



Additionally, the comparison of scenarios allowed the contrasting of certain aspects like data availability of both sectorial and sustainable PRPs and how they affect the analysis of the process's social performance. In compiling the inventory for PRPs, it was observed that there are availability limitations at site-level, especially for indicators intrinsically related to socio-economic aspects. Indicators related to technical parameters such as resource consumption (e.g., energy and water), CO_2 emissions (scopes 1 and 2), or accident rates like TRIR (total recordable incident rate) have a greater number of performance data, and the format used (units and quantification methods) shows better consistency. In the case of socio-economic indicators, there are inconsistencies with the information presented in corporate reports; not all companies present information in the same indicators, or some do not report at all. Some cases such as information on contributions to communities and investment in R&D show the greatest variety; many reports fail to clearly mention data in these aspects. When establishing PRPs based on SDGs, this trend continues: indicators related to technical aspects have a specific goal (a specific numerical value) that companies and the sector in general have accepted. These goals are based on physical aspects that are rigorously quantified considering trends or technological, economic criteria, among others. In contrast, indicators more intrinsically associated with social performance, such as investment in communities or the number of committees, do not have these specific goals. Many of these are tied to laws or policies of each location, which ultimately depend on the culture or perception of the responsibility companies have towards society. For this reason, when analyzing both scenarios, it is observed that for five indicators, there is no change; meaning that PRPs based on the current sector's performance and those derived from the SDGs are the same. In this case, these socio-economic goals must be proposed or suggested by the analyst but are subject to possible inconsistencies and uncertainties.

In Figure 9, the comparison of the overall social performance of the PVC suspension production process is shown when modifying sectoral PRP to PRP based on goals derived from the Sustainable Development Goals (SDGs). It is observed that in the pessimistic

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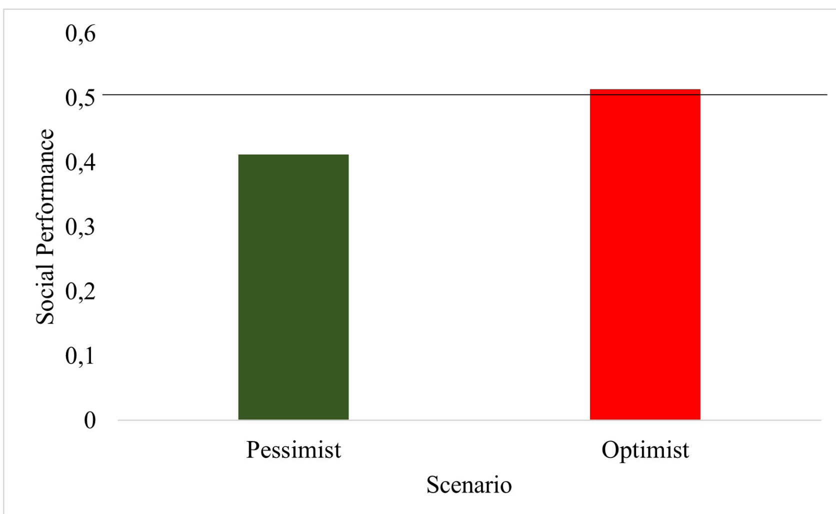
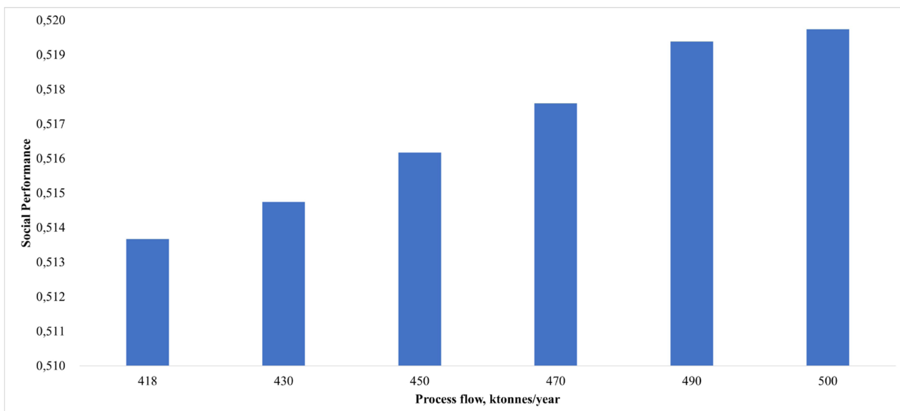
scenario, the performance of the plant in Colombia decreases to 0.412, representing a 24% decrease compared to the optimistic scenario. This places the process performance in the non-compliance but improving category compared to the optimistic scenario. The reduction is expected considering that many of these goals are set to be achieved by 2025, 2030, or 2050, taking into account limitations such as technological, infrastructural, political, among others (Objetivos de Desarrollo Sostenible, 2015). Additionally, the evaluation of social performance under more rigorous social sustainability criteria, demonstrated that although it does not reach conformity (as it is below 0.5), it is close to that level, which is positive. This indicates that the strategies being implemented by companies currently yield results that are moving in the right direction towards a more socially sustainable industry. This is particularly relevant given the crucial value that sustainable operations (economic, environmental, technical, and social aspects) have gained in the competitiveness of chemical processes, especially in countries like Colombia that seek to improve quality of life by expand their participation in the global economy through (re) industrialization (like developing countries).

Figure 9. *Overall social performance of a suspension PVC production plant in Colombia under optimistic and pessimistic scenarios.*



In Figure 10, the effect of production capacity on the social performance of the PVC suspension production plant located in Colombia is depicted. Employment potential was selected to study the effect of increased production flow. It is evident that there is a direct positive relationship between increased flow and the social performance of the process; as the flow increases, more personnel will be required on-site to perform tasks to keep the new process units operational. With a process flow of 500 tons per year, the social performance of the process increases by 1%. If the weighting factor of this indicator is higher, the effect of the increased performance of the indicator may be more decisive. Additionally, Pillain et al. suggest that it is possible to increase the employment potential of a process by harnessing valuable wastes. If there is a significant flow of usable material, this indicates, through new operating units (Pillain et al., 2019), that the adoption of integration strategies would result in a significant increase in social performance, which should be explored.

Figure 10. *Effect of production flow on the social performance of the PVC plant located in Colombia.*



5. Conclusions

The new demands on the plastics industry for sustainable products by consumers have generated the need to assess and optimize processes under sustainability considerations such as

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social performance. The study provides an assessment of the social performance of a PVC suspension production plant when considering two different locations (Colombia and Belgium). For this, social analysis was supported by a theory of change. The combined analysis of s-LCA and the theory of change reveals a positive social performance score for both locations, exceeding conformity (above 0.5). Upon delving into the results of the social life cycle analysis, a notable distinction in social performance is observed between PVC production plants located in Colombia and Belgium. In particular, the plant in Belgium exhibited superior performance in terms of working hours and number of vacation days, possibly reflecting a more rigorous regulatory framework and higher corporate social awareness. However, aspects associated with communities and society show regular performance due to impacts related with the use of natural resources. Both sites demonstrated areas for improvement in interacting with local communities, suggesting the need for more integrated strategies addressing the use of natural resources and their impact on local well-being. Furthermore, a sensibility analysis was conducted by varying the PRP and the functional unit (from 418,000 t/year to 500,000 t/year). The first analysis showed that when comparing process performance to development goal-based targets, process performance (for the Colombian case) decreases by 24% but remains close to conformity (0.44). These results underscore the importance of considering the socio-economic and regulatory context in which production plants operate to identify effective strategies that improve their overall social performance. Indicators for local communities are the most affected, with a decrease of up to 60%. Additionally, it was found that purely social indicators provide less quantitative information compared to purely technical indicators. For the analysis of the effect of production capacity, it was found that an increase in process flow has positive repercussions on the social impacts of the process due to an increase in the plant's workforce. Finally, the adoption of sustainable and responsible practices not only benefits communities and the environment but also reinforces the resilience and competitiveness of industrial operations in the long term.

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