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Dynamics of production of greenhouse gases in the sectors of steel production and vehicle production

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Dynamics of production of greenhouse gases in the sectors of steel production and vehicle production

Abstract: The foundry sector and the automotive sector are a source of greenhouse gas emissions. Understanding the relationships and dynamics between the two sectors allows designing better strategies that seek to reduce greenhouse gas emission levels and thus achieve mitigation of climate change. Given that the dynamics of a sector are influenced by its own dynamics and the dynamics of the other, also subject to growth limits, the objective of this document is to design a system that represents the interaction between the steel foundry sector and the automotive sector, which allows to identify the dynamics in terms of generation of greenhouse gases.

The results show interdependence between the sectors, which is determined by the dynamics of economic growth and has an impact on higher CO_2 levels. In addition, the dynamic hypothesis proposed is true, which allows us to establish that economic growth can be associated with higher levels of CO_2 emission. Modeling with complex dynamics is essential to understand the dynamics and interrelationships between sectors and their impact on the levels of greenhouse gases, which allows a better design of the measures that seek to reduce the levels of greenhouse gas emissions and mitigate climate change.

Keywords: Dynamic systems; greenhouse gases; modeling; steel production; vehicle production.

Dinámicas de producción de gases de efecto invernadero en los sectores de acero y de vehículos

Resumen: El sector de fundición y el sector automotriz son fuente de emisiones de gases de efecto invernadero, entender las relaciones y dinámicas entre ambos sectores permite diseñar mejores estrategias que busquen reducir los niveles de emisión de gases de efecto invernadero y así lograr la mitigación del cambio climático. Dado que la dinámica de un sector está influenciada por la dinámica propia y la del otro, sujeto también a límites de crecimiento, el objetivo de este documento es diseñar un sistema que represente la interacción entre el sector de la fundición de acero y el sector de la automoción lo que permite identificar la dinámica en términos de generación de gases de efecto invernadero.

Los resultados muestran una interdependencia entre los sectores, que está determinada por la dinámica del crecimiento económico y tiene un impacto en niveles más altos de CO_2. La modelación con dinámicas complejas es fundamental para comprender la dinámica e interrelaciones entre sectores y su impacto en los niveles de gases de efecto invernadero, lo que permite un mejor diseño de las medidas que buscan reducir los niveles de emisiones de gases de efecto invernadero y mitigar el cambio climático.

Palabras clave: sistemas dinámicos; gases de invernadero; modelado; producción de acero; producción de vehículos.

Dinâmica de produção de gases de efeito estufa nos setores de produção de aço e de produção de veículos

Resumo: O sector da fundição e o sector automóvel são uma fonte de emissões de gases do efeito estufa, compreender as relações e dinâmicas entre os dois sectores permite desenhar melhores estratégias que procurem reduzir os níveis de emissões de gases do efeito estufa e assim alcançar a mitigação das alterações climáticas. Dado que a dinâmica de um sector é influenciada pela sua própria dinâmica e pela dinâmica do outro, também sujeita a limites de crescimento, o objectivo deste documento é desenhar um sistema que represente a interacção entre o sector da fundição de aço e o sector automóvel, o que permite identificar a dinâmica em termos de geração de gases do efeito estufa.

Os resultados mostram a interdependência entre os setores, que é determinada pela dinâmica do crescimento económico e tem impacto em níveis mais elevados de CO_2. A modelação com dinâmicas complexas é essencial para compreender a dinâmica e as inter-relações entre os setores e o seu impacto nos níveis de gases do efeito estufa, o que permite um melhor desenho das medidas que procuram reduzir os níveis de emissões de gases do efeito estufa e mitigar as alterações climáticas.

Palavras-chave: Sistemas dinâmicos; gases efeito estufa; modelagem; produção de aço; produção de veículos.

Introduction

The foundry sector and the automotive sector have been identified as an important source of greenhouse gas (GHG) emissions, especially carbon dioxide (CO_2) (Intergovernmental Panel on Climate Change [IPCC], 2022). For the foundry sector, the work of Vogl *et al.* (2018) establishes that steel production represents approximately 7% of global carbon dioxide emissions. For Hasanbeigi *et al.* (2014), the iron and steel industry accounts for around a quarter of global industrial sector GHG emissions, and around 8% of global final energy demand and 7% of CO_2 emissions from the energy sector, including process emissions (Shatokha, 2015). For its part, for the vehicle sector, works by Wallington *et al.* (2008) and Şanlı *et al.* (2021) identify volumes of CO_2 emitted by vehicles and its effect on climate change.

To analyze emission dynamics, different models have been developed using a wide range of level of detail in order to represent or predict the level of emissions (Ramin & Huhtanen, 2012; Giltrap *et al.*, 2010; Powlson *et al.*, 1996; Del Prado *et al.*, 2011; Chianese *et al.*, 2009 and Del Prado *et al.*, 2011). However, the existing models are generally simple models that range from considering both emission factors in isolation to empirical relationships. However, to fully represent the dynamics of a system and its influence, models must integrate the combined effects and their interrelationships. In this sense, the objective of this document is to design a complex dynamics model that allows identifying the interrelationships, and main components, in this case, between the foundry sector and the automotive sector and their influence on CO_2 emission levels. The purpose of this document is to build a model that allows simulating said dynamics through system dynamics.

As a dynamic hypothesis, it is established that if income increases, the demand for vehicles increases, leading to an increase in the demand for steel as an input, as well as an increase in the production of vehicles that, when used, increase the emission and therefore accumulation of GHG (greenhouse effect).

It is proposed that the production dynamics of the steel foundry sector is influenced by its own dynamics and by the dynamics of the automotive sector, given that vehicle production is fed by the steel industry. But the steel sector is subject to growth limits based on the natural limit of raw material availability and that the recycled steel used in production is losing quality. This creates a dynamic between both populations, especially in the accumulation of GHG, whose behavior we seek to describe through system dynamics.

According to the United Nations Organization in relation to climate change, there is an upward trend related to the emission of GHG, which in the period 2000-2022 has reached a peak of 37,490,000,074 tons reached in 2022. However, there was a decrease for the period 2019-2020, due to confinements during the pandemic period, and in the period 2009-2010, which responds to the global financial crisis that began with the bursting of the real estate bubble in the United States (Figure 1).

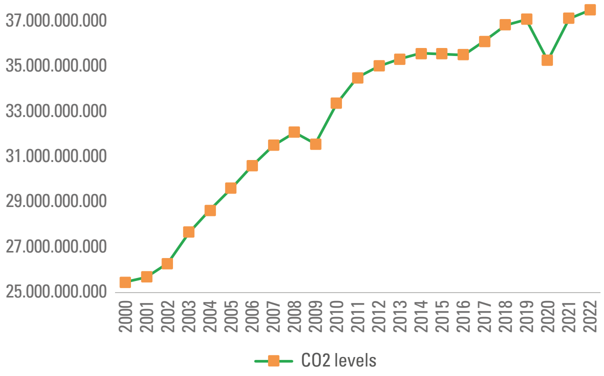

Figure 1. Accumulated CO_2 levels (in tons) in the period 2000 to 2022

Source: Own elaboration based on https://ourworldindata.org.

Figure 2 shows the world production of vehicles on the right axis and the world production of steel on the left axis in the period 2009 to 2020. Based on Rietmann *et al.* (2020) in relation to the world production of vehicles, a growing trend can be seen, as well as a contraction since the beginning of 2018 due to economic conditions and a contraction in the pandemic period.

For its part, according to Ravazzolo & Vespignani (2020), steel production in the automotive sector has high demand due to the mechanical and physical properties of steel, which is used in the production of parts such as engines (crankshafts, shafts. cams, pistons), brake system (discs), and bodies (chassis and parts to support the doors), among others.

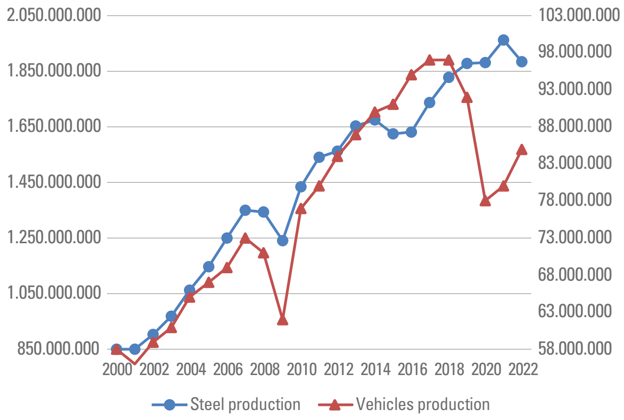

Figure 2. Tons of steel produced (left) and number of vehicles produced (right) in the period 2000 to 2022

Source: Own elaboration based on worldsteel.org and https://www.statista.com.

Globally, production in the period 2009-2020 presents an increasing trend, despite the drop in the period 2015-2016 explained by the global drop in production due to economic conditions in China and Brazil; however, production recovered its upward trend.

This document is divided into three parts, the first presents the introduction, where a characterization of the foundry sector, vehicle production, and CO_2 emission levels is made. In the second part, a description of the complex dynamics model to be implemented is made, where the variables, equations and parameters are described and represented by the Forrester Diagram. In the third part, the results and discussion of these are presented in the context of the literature, where the hypothesis is confirmed, and finally the conclusions are presented.

Methodology

The complex dynamics model developed in this section is based on the work of Ding *et al*. (2016), Aracil and Gordillo (1997), Ibarra-Vega (2016), and Bayer (2004). The complex dynamics model is a representation of the dynamic behavior of a system, where it seeks to transfer the characteristics of the real system to an artificial representation. This allows us to conceive the production structures of steel production and vehicle production as a set of elements that interact with each other, assuming that there is a mutual influence between their elements. To completely describe the system, it is necessary to know its elements (structure) and interactions, its states and its transitions (dynamics), through flow diagrams.

As a first step, the elements that condition the behavior of both sectors will be identified and organized together with their relationships. This is necessary because the dynamics of each sector will be represented not in isolation, on the contrary, showing the interaction, but mainly identifying the feedback of the sectors, which form feedback loops that can be key when establishing solutions to mitigate the emission of GHG. Subsequently, a flow diagram will be drawn (Figure 3) identifying levels, flows and auxiliary variables to be able to carry out the simulation. As a first step, the elements that condition the behavior of both sectors will be identified.

Figure 3 presents the Forrester Diagram on the dynamics and interdependence between the sectors of steel production, vehicle production and CO_2 accumulation, where an interdependence between the sectors is presented given that the inputs of one are the base of the production of the other. But there are natural limits depending on the available production, which creates a dynamic between both populations that ultimately end up increasing CO_2 levels.

Natural capacity refers to the natural limit that exists based on the stock of iron available in nature to obtain steel, that is, a natural limit given that the iron from which steel is obtained is a finite resource, according to the United States Geological Survey. Gross iron ore reserves are estimated at 180 billion metric tons by 2022. This figure will be the initial value in the model for the Natural Capacity variable.

According to Kirschen *et al*. (2011) and Da Silva *et al*. (2008), iron is taken from the mine (which contains pure iron ore or ore, as well as impurities or gangue)

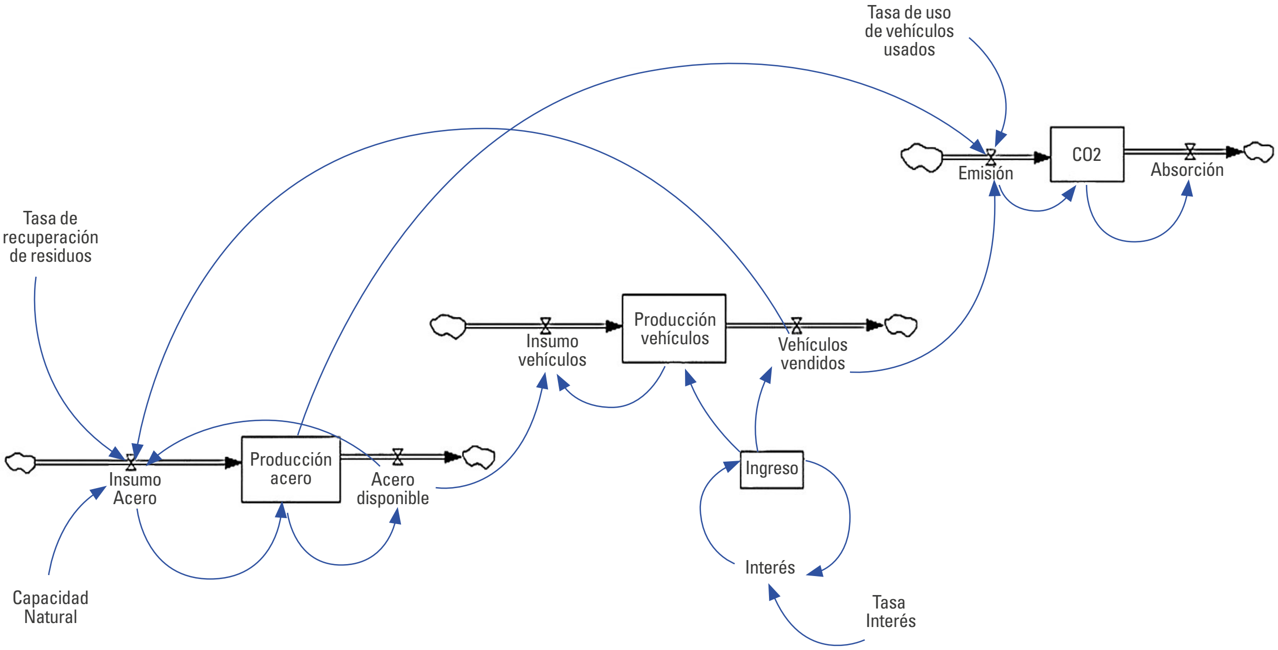

Figure 3. Forester diagram of the dynamics and interdependence between the sectors of steel production, vehicle production and CO_2 accumulation.
Source: Own elaboration.

to make steel, and together with the fuel called 'cok' are processed in a blast furnace, with the aim of eliminating impurities. Since steel scrap can also be added in this process, in order to reuse it, in this combustion process the carbon joins the steel and the 'cok', and liquid steel is formed, which goes to the molding process. According to Araújo and Schalch (2014), 98% of steel scrap is recycled, therefore, the waste recovery rate will initially be 98%.

The dynamics of steel production is taken as a stock variable formed by two flows that are: i) the availability of inputs, and ii) the flow of steel available for sale to productive sectors such as construction. The relationship between these two systems is given because the production of vehicles depends on the availability of steel for steel parts for vehicles. But the development of vehicles will depend on the dynamics of production worldwide; so, the greater the growth, the more employment and greater resources to acquire goods and services.

This dynamic will be influenced not only by the natural dynamics of production and sales, but also due to the dynamics of the economy in general. The greater the growth and the expectation of future growth, the greater the demand for vehicles, therefore, the greater the demand for the steel necessary for their production.

Likewise, the dynamics of CO_2 production is taken as a stock variable formed by two flows that are the emission of CO_2 and the absorption flow of CO_2. Based on Van Marle *et al*. (2022), it is estimated that approximately 65% of gas emissions are carbon dioxide and that this comes from industrial sectors such as cement, steel and transportation production. Absorption is understood as a process where molecules of one substance are trapped or retained on the surface of another. According to Terrer *et al*. (2021), this process is carried out by terrestrial ecosystems by 30%, especially forests, plants through photosynthesis and the oceans through plankton.

Table 1, Table 2 and Table 3 present the model equations, as well as the auxiliary variables and the values of the parameters with which the model simulation was carried out.

Table 1.
Model equations

Variable	Initials	Unit	Equation
Steel production	PnAc	Ton	PnAc = IA - AD
Vehicule production	PnVh	Ton	PnVh = IV - VV
CO_2 production	$PnCO_2$	Ton	Production of CO_2 = Emission - Absorption
Steel input	IA	Ton	IA = CapNat + AD * TasRecRes + VV * TasRecRes + AD*TasAceOtro
Steel available	AD	Ton	AD = PnAc
Vehicle inputs	IV	Ton	IV = AD*0.3
Vehicles sold	VV	Ton	VV = PnVh
CO_2 emission	ECO_2	Ton	ECO_2 = VV*0.3
CO_2 stock	SCO_2	Ton	$SCO_2 = ECO_2 - ACO_2$
CO_2 absorption	ACO_2	Ton	$ACO_2 = TasAbsCO_2*NCO_2$

Source: Own elaboration.

Table 2.
Auxiliary variables

Variable	Initials	Unit	Source
Waste recovery rate	TasRecTes	Ton/Month	Average actual data
Used vehicle usage rate	TasUsoRes	Ton/Month	Time
Rate of vehicles sold	TasVehVen	Ton/Month	Average actual data
Available steel rate other sectors	TasAceOtros	Ton/Month	Average actual data
CO_2 absorption rate	$TasAbsCO_2$	Ton/Month	Time
Income	Ingre	Ton/Month	Increasing function

Source: Own elaboration.

Table 3.
Model parameters

Variable	Initials	Unit	Value
Natural iron supply capacity for steel	CapNat	Ton	1,639,333,333
CO_2 level	NCO_2	Ton	37,490,000,074

Source: Own elaboration.

Results

A period of 100 years has been simulated between t = 0 and t = 100 using the fourth order Runge-Kutta as a numerical approximation method and with a weight of h = 0.015625. To better approximate the model, we start from levels and growth rates obtained from historical data.

The first strategy consisted of varying the rate of economic growth. To develop this strategy, the variable growth rate was implemented in the model since it is assumed that economic growth is associated with the living standards of modern society, where technology and the consumption of certain goods such as health, education, housing, etc., are synonymous with well-being. This condition is incorporated into the model assuming that an increase in income implies generation of employment. Higher income leads to an increase in the demand for goods among these vehicles, which leads to an increase in the demand in the steel production sector for material for the production of parts, and to higher emission levels. Likewise, an increase in demand for vehicles implies greater pollution due to the emission generated by the combustion of vehicles.

Movements in the economic growth rate were made from values close to 0, then values close to 0.5 and subsequently values close to 1. The CO_2 emission curve was expected to have a positive slope as the rate of economic growth increases. This is because an improvement in economic conditions leads individuals to consume goods such as personal vehicles, which impacts CO_2 emissions. On the one hand, the demand for steel inputs and materials to produce vehicles increases, and in the steel production process CO_2 emissions are generated in the blast furnaces; and on the other hand, when the vehicles are used CO_2 emissions are generated in engine combustion.

The results allow us to verify the hypothesis and are presented in Figure 4. It is found that the CO_2 levels start from an initial level given by exogenous factors. However, as the economic growth rate increases, its trend is increasing, depending on the emission generated in the production of parts for vehicles; likewise, the combustion generated by vehicles increases, which means that the rate of economic growth plays a role in CO_2 emission levels.

The second strategy consisted of implementing the usage rate of used vehicles. For the development of this strategy, the variable 'usage rate of used vehicles' was implemented in the model, which indicates an emission level given the increase in the extension of the useful life of vehicles. Especially in low-income regions, these vehicles do not incorporate technological advances that achieve lower combustion and therefore lower emissions.

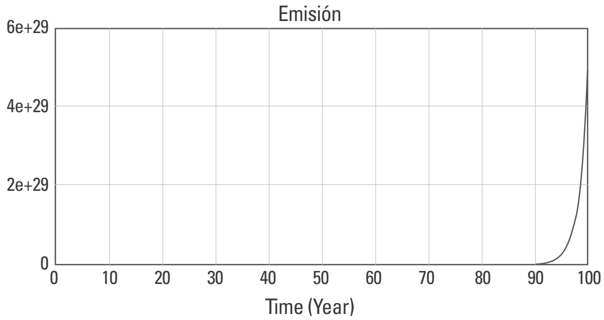

Figure 4. Results of the analysis of movements in the economic growth rate and its impact on the system in general

Source: Own elaboration.

Movements were made in the usage rate of used vehicles from values close to 0, then values close to 0.5 and subsequently values close to 1. It was expected that the CO_2 emission curve would have a positive slope as the usage rate increases the use of used vehicles. This is because the engines of old vehicles do not incorporate technologies that achieve greater power and performance from lower consumption of fossil energy, and their emission volumes are higher compared to electric, hybrid, or hydrogen engines.

The results allow us to verify the hypothesis, and indicate that the CO_2 levels start from an initial level given by exogenous factors. This level can be observed close to 150 million tons in the model (in Figure 5, the level of the red line). However, as the usage rate of used vehicles increases the level rises to 150 million tons (in Figure 5, the level of the blue line). This can be explained by the increase in combustion generated by vehicles with less efficient engines, which means that the usage rate of used vehicles plays a role in CO_2 emission levels after modeling. Subsequently, it can be observed that in Figure 5 both the red and blue lines present a decreasing trend, which can be explained by the obsolescence of the vehicles that would be no longer used, for which they would no longer generate CO_2 emissions.

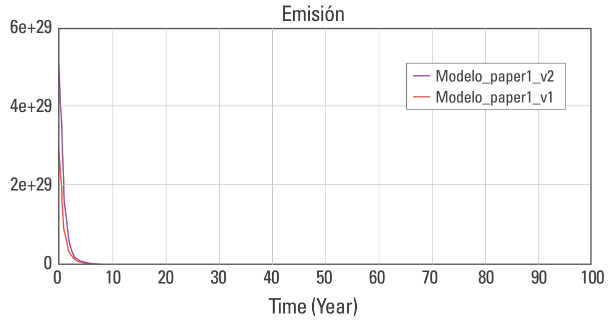

Figure 5. Movement analysis results on the usage rate of used vehicles and its impact on the overall system

Source: Own elaboration.

The third strategy consisted of the implementation of the steel recovery rate. To develop this strategy, we implemented in the model the steel recovery rate variable, which indicates the recycling level of recycled steel that comes from waste generated in other industries.

Movements of the steel recovery rate were made from values close to 0, then values close to 0.5 and subsequently values close to 1. It was expected that the CO_2 emission curve would have a negative slope as the recovery rate of steel increases; this, because it reduces the need to process ore and generate gas emissions as a result of the combustion generated in the blast furnaces.

The underlying logic is that CO_2 levels start from an initial level given by exogenous factors. However, as the steel recovery rate increases, its trend is decreasing, depending on the decrease in pressure due to the need to process more iron material to produce steel, which means that the steel recovery rate plays a role in the CO_2 emission levels. After doing the modeling, we can determine that as the steel recovery rate values increase, the GHG emission levels are reduced (Figure 6).

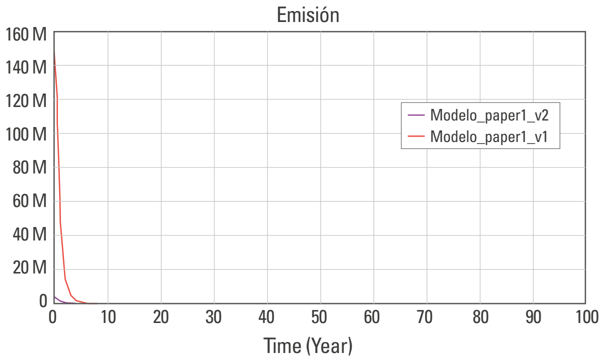

Figure 6. Results of the movement analysis on the steel recovery rate and its impact on the overall system

Source: Own elaboration.

Discussion

After carrying out the modeling, in relation to the economic growth rate, based on the results the hypothesis can be corroborated. The analysis starts from identifying the natural or initial behavior of the system, the levels of the variable 'economic growth rate' were initially analyzed, taking values close to 0, and it was observed that the CO_2 emission values remained at levels close to 160 million tons (in Figure 6, red line). Subsequently, the levels of the economic growth rate were increased by 50%, the CO_2 emission rates also increased, and subsequently the economic growth rates were located at values close to 1, where it is observed that the CO_2 emission values decreased to around 5 million tons of CO_2 (in Figure 6, blue line).

In general, after analyzing the three scenarios, we can determine that the dynamic hypothesis is confirmed. The strategy for the implementation of complex dynamics allows us to identify relationships and fundamental variables that help the design of strategies to guide the reduction of GHG. In this case, the economic growth variable determines the dynamics of vehicle consumption, and in this way both sectors are energized, because with more income, the demand for vehicles increases, and so the demand for steel increases with the consequence of an increase in emission levels from both steel smelting and vehicle use.

Based on the analysis of Abramovitz (1989), Ding (2012), Jackson and Marks (1999, and Yeh and Hartmann (2021), the behavior exhibited can be associated with the fact that the variable rate of economic growth is associated with the living standards of modern society, where technology and the consumption of certain goods is synonymous with well-being. Therefore, this condition is incorporated into the model assuming that an increase in income implies greater demand on the part of individuals, which leads to an increase in the demand for workers. This way, we would have more jobs with a reasonable salary that can lead to an increase in the demand for goods, including vehicles, which implies an increase in demand from the steel production sector for materials for the production of parts, and, therefore, higher emission levels. Likewise, an increase in demand for vehicles implies greater pollution due to the emission generated by the combustion.

Additionally, the used vehicle usage rate strategy indicates an emission level given the increase in the extension of the useful life of vehicles, which is in line with what was established by Köne & Büke (2010). Especially in low-income regions, these vehicles do not incorporate technological advances that achieve better combustion that reduces emission levels. This is because the engines of old vehicles do not incorporate technologies that achieve greater power and performance from lower consumption of fossil energy, and the emission volumes are higher compared to electric, hybrid, or hydrogen engines. Therefore, not taking action with the stock of used vehicles implies maintaining high CO_2 emission levels that do not allow us to mitigate global warming.

Therefore, taking into account that strategies 1 and 2 are based on the use of personal vehicles, with the objective of seeking to reduce CO_2 emissions, the variables play a fundamental role, since the personal vehicle consumption dynamics associated with higher levels of income generated by economic growth must be reduced by having a greater offer of more sustainable mobility.

In this context, and following Canals-Casals *et al*. (2016) and Rietmann *et al*. (2020), alternative actions to the use of individual vehicles are necessary. Strategies such as promoting sustainable public mobility, or the increase of the useful life of used environmentally friendly vehicles, reduce the demand for personal vehicles and therefore the demand for steel products. In this way, it is necessary to design parts that require recycled components, as well as the design of more efficient vehicles that contain other types of materials with a greater component of recycled plastic, which reduces weight and the need for strength and combustion.

For its part, the analysis of the third scenario increases the recovery rates of steel waste. Following Terrer *et al*. (2021), the variable steel recovery rate indicates the recycling rate of surplus or recovered steel, which comes from steel waste generated in other industries. Based on Xu and Cang (2010), Holappa (2020) and Da Silva *et al*. (2008), by increasing the waste recovery rate the need to process ore and generate gas emissions as a result of the combustion generated in the blast furnaces is reduced. However, as indicated by Araújo & Schalch (2014), steel recovery levels are around 98%, so this variable would already be at its optimal maximum. Therefore, other alternatives must be sought to reduce demand of raw materials to avoid the melting of blast furnaces.

In general, the relationship associated with the fact that the steel production sector is linked to the automotive production sector is confirmed through the offer of material manufactured in the form of parts to be molded, according to the requirements in the automotive sector. However, there are other links that go from the supply of waste from the automotive sector to the steel production sector to be recycled in the foundry sector. This is essential because by increasing the disposal of material the need for extraction of iron would be reduced, both with its smelting process, which reduces the emission of GHG.

Another feedback process is generated by automotive demand towards the steel production sector. Since there is a demand for environmentally friendly vehicles, including vehicles with materials that use recycled plastic, the demand for steel products is reduced, which reduces production and therefore the emission of GHG resulting from the foundry.

Conclusions

The socio-economic system described to analyze the CO_2 emissions from the dynamics of the steel and vehicle production sectors, described from the complex dynamics, allows the analysis of causal relationships and shows how in their natural or initial state they are generated, considering CO_2 emissions due to factors exogenous to the model.

Based mainly on the growth of the economy, CO_2 emission levels increase significantly, which is why it is established that the dynamic hypothesis proposed is true, which allows us to establish that economic growth can be associated with higher levels of CO_2 emission.

In this context, alternative actions to the use of individual vehicles are necessary, in which promoting sustainable public mobility, or the increase in the useful life of used environmentally friendly vehicles, reduces the demand for personal vehicles and therefore the demand for steel products. In this way, it is necessary to design parts that require recycled components, as well as the design of more efficient vehicles that contain other types of materials with a greater component of recycled plastic, which reduces weight and the need for strength and combustion.

Likewise, from the analysis of the impact on the system of the usage rates of used vehicles, it is evident that they have a positive impact on the increase in CO_2 emissions. This is why it is established that the dynamic hypothesis proposed is true, which allows us to establish that the usage rates of used vehicles can be associated with CO_2 emission levels.

When analyzing the strategy aimed at reducing CO_2 emissions such as the recycling of steel materials, from the analysis of the recovery rates of steel waste, it is evident that they have a positive impact on the reduction of CO_2 emissions. The latter occurs due to lower pressure on the production of new steel, which reduces the processes in the blast furnaces. Therefore, it is established that the dynamic hypothesis proposed is true, which allows us to establish that the recovery rate of steel waste can be associated with CO_2 emission levels.

Finally, it was evident that the production dynamics of the steel foundry sector are influenced by its own dynamics and by the dynamics of the automotive sector, given that vehicle production is fed by the steel industry. But the steel sector is subject to growth limits based on the natural limit of raw material availability and that the recycled steel used in production is losing quality. This creates a dynamic between both populations, especially in the accumulation of GHG, whose behavior can be described through system dynamics.

This study has relevance in terms of sustainability, expressed in identifying variables that allow policy actions to be taken in search of mitigating global warming. Also, since it identifies the variables that generate dynamics between the two sectors such as economic growth and its impact on increasing emission levels. This study increases existing knowledge, strengthens methods and supports existing studies. Its use is general and can be applied at a particular level. Likewise, it has great methodological utility by innovating in methods that allow the dynamics of a system to be thoroughly represented; their interrelationships and influence in different contexts, and allow their modeling to evaluate various possible scenarios.

According to the conclusions, the variable 'economic growth' energizes the steel and vehicle production sectors. It is necessary to analyze the impact of policies such as changes in mobility towards mass transportation systems, and the design of efficient and compact cities.

The socio-economic system described to analyze CO_2 emissions from the dynamics of the steel and vehicle production sectors underscores the intricate web of causal relationships that govern environmental impact. Initially, both sectors exhibit substantial CO_2 emissions driven by factors external to the model, primarily linked to economic growth. This reinforces the validity of the dynamic hypothesis, affirming the correlation between economic expansion and heightened CO_2 emissions.

In addressing this challenge, alternative strategies are imperative to mitigate individual vehicle usage. Promoting sustainable public transportation and extending the lifespan of environmentally friendly vehicles can curtail the demand for personal automobiles and subsequently reduce the need for steel products. To further alleviate the environmental strain, the design of vehicle components should prioritize recyclable materials, such as recycled plastics, thereby minimizing weight and reliance on combustion.

Moreover, the analysis highlights the positive correlation between the utilization rates of pre-owned vehicles and CO_2 emissions, affirming the dynamic hypothesis. Policies targeting CO_2 reduction, such as steel recycling initiatives, demonstrate tangible benefits. Higher rates of steel waste recovery alleviate pressure on new steel production, thereby diminishing CO_2 emissions associated with manufacturing processes. This bolsters the notion that the recovery rate of steel waste directly influences CO_2 emission levels.

Furthermore, the study elucidates the intertwined dynamics between the steel and automotive sectors. While vehicle production drives demand for steel, the steel industry faces constraints due to finite raw material availability and diminishing quality of recycled steel. This symbiotic relationship underscores the necessity for comprehensive system dynamics modeling to accurately capture their interplay and subsequent GHG emissions.

This research holds significance for sustainability efforts by pinpointing actionable variables for policy interventions aimed at mitigating global warming. By elucidating the impact of economic growth on emission levels and proposing strategies like mass transportation and compact city design, this study contributes to the body of knowledge on environmental management.

In conclusion, this study underscores the imperative of holistic approaches to address CO_2 emissions from industrial sectors. By identifying key variables and proposing viable interventions, it enriches existing methodologies and informs policy decisions geared towards sustainable development.

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