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# Sustainability transition of production systems: A longitudinal study investigating regenerative manufacturing attributes

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**Abstract**

Regenerative manufacturing presents a new paradigm for production systems, moving beyond traditional sustainability by aiming for positive, large-scale impact across the value chain. Rather than simply minimizing harm, it seeks net positive value for stakeholders by fostering the co-evolution of industry, society, and nature. Despite rising interest, theoretical and practical understanding of how to integrate regenerative manufacturing into industrial systems—especially in the Global South—remains limited. This study identifies key attributes of regenerative manufacturing and analyses historical data from a Global South country. Four main attributes emerged from an in-depth literature review: integration with natural ecosystems, circularity and systemic value, social justice and production ethics, and learning and adaptation capacity. These were examined through a longitudinal analysis of secondary data from Brazil, using the multilevel perspective (MLP) to map interactions among niche innovations, socio-technical regimes, and landscapes. The findings show that Brazil has not made sufficient progress toward a new sociotechnical regime for regenerative manufacturing, highlighting the need for better alignment between emerging technologies and public policy. The study's main contribution is the identification and empirical assessment of regenerative manufacturing attributes using the MLP, providing guidelines for industrial transitions toward regenerative manufacturing.



*Keywords:* MLP, regenerative manufacturing, sustainability transition, longitudinal study, sustainable development, Global South.

## 1. Introduction

The search for more responsible industrial solutions in the face of intensifying climate crises, biodiversity loss, and increasing social inequalities has fueled the debate on the urgency of rethinking traditional production models. It is no longer enough to reduce negative impacts; it is necessary to adopt approaches capable of regenerating the natural and social systems affected by human activities[1]. In this scenario, regenerative manufacturing proposes the transformation of industrial systems through the integration of circularity, social justice, environmental restoration, and technological innovation[1], [2], [3], [4]. More than a simple evolution of traditional sustainability, this approach aims to restore ecosystems, revitalize communities, and generate net positive impacts throughout the value chain[5], [6].

Yet, the conceptualization and implementation of regenerative manufacturing in industrial contexts remains unclear. Recent literature has advanced discussions in the conceptual realm[1], [5], [6], yet a systematic delineation of the


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defining attributes of this paradigm remains elusive. This deficiency hinders the comprehension, practical implementation, and incorporation of the concept of regenerative manufacturing into coherent industrial strategies. In addition to the conceptual deficit, there is an absence of empirical research that would link attributes of regenerative manufacturing with historical indicators. The implementation of longitudinal studies is particularly limited in countries of the Global South, a category that includes Brazil. This limitation hinders the capacity to provide a critical and contextualized assessment of whether practices have genuinely progressed towards models of regenerative production.

Thus, the present research delineates the following research objectives (RO): (RO1) Determine the attributes necessary for effective characterization of the concept of regenerative manufacturing; and (RO2) Analyse historical data in relation to the identified attributes, considering the Brazilian context. To support this analysis, we employ the Multilevel Perspective (MLP) proposed by Geels[7], which enables us to examine the dynamics of sustainability transition through the interaction between innovation niches, sociotechnical regimes, and landscapes. This research contributes in two distinct ways. On a theoretical level, the study advances the conceptualization of regenerative manufacturing through the systematization of key attributes. From a pragmatic standpoint, it offers a framework for evaluating industrial policies and practices in emerging countries, where the challenge of reconciling economic development and environmental regeneration is particularly critical.

## 2. Theoretical framework

The theoretical framework was structured into two complementary interrelated domains: (1) Multilevel perspective (MLP) and (2) Regenerative manufacturing.

### *2.1. Multilevel perspective (MLP) for sustainability transition*

One way to better understand the sustainability transition to regenerative manufacturing is through MLP (Multilevel Perspective). MLP is a theoretical approach that stands out in the academic debate on social transformations aimed at sustainability[8]. This perspective seeks to understand transitions in socio-technical systems. It recognizes the complexity of transitions, incorporating the multidimensionality of processes and the actions of multiple actors at different spatial and temporal scales [9].

The MLP is structured around three interrelated analytical levels: niche innovations, socio-technical regimes and landscape [7]. These levels are interrelated through multilevel interaction dynamics and variables over time in three phases [8]. In the first phase, radical innovations emerge in small niches on the periphery of existing systems through the pioneering activities of entrepreneurs, startups, activists or other outsiders [8] triggering a cascade of technical and institutional changes that may eventually transform the broader architecture of the system [10]. Actors in niches hope that their innovations may eventually be used in the regime or even replace it [11]. However, this is not easy, given that the existing regime is stabilized by many mechanisms of entrapment[12]. In the second phase, the socio-technical regime represents the dominant structure of a system and consists of six interconnected elements: culture, technology, industry, science, politics, and the market [7], [13]. These components stabilize existing practices and often impede changes towards sustainability. In the third phase, the landscape level refers to the macro level of the structure [9]. It comprises multiple exogenous components and the surrounding external environment for interactions between actors at the regime and niche levels [14]. These elements are beyond the direct control of actors, but they influence the regime and niche levels by creating pressures and opportunities for change [13]. Such pressures can generate windows of opportunity for regenerative practices to take hold, provided they are interpreted and responded to by key actors [15], [16]. It is worth highlighting that the relationship and interactions between the levels are flexible and dynamic.

### *2.2. Regenerative manufacturing and its attributes*

The concept of regeneration, originating in the biological sciences, refers to the ability of organisms, cells and ecosystems to continuously renew themselves [17], [18]. The term "regenerating" is defined as "making it better" than its original condition [19]. Middleton et al.[20] reinforce this view by stating that the term "regenerative" refers to processes that restore, renew, and revitalize their own sources of energy and materials, promoting sustainable systems that balance the needs of society with the integrity of nature.

In this context, regenerative manufacturing emerges as an innovative approach that applies the principles of regeneration to industrial production. This approach is not limited to mitigating environmental damage, but also strives to rejuvenate and reinvigorate ecosystems, communities, and economies [2] leading the industry to go beyond “doing less harm” to “doing more good,” that is, going beyond “zero impact.” [1]. Thus, organizations with regenerative business models focus on planetary health and social well-being by creating and delivering value at various stakeholder levels [6], [21]. Although some industries depend more on nature than others, any industry can and should adopt regenerative thinking [6]. It is worth noting that regenerative development is not limited to operational changes but involves a process of change to sustain living systems and thriving communities [4]

To better operationalise regenerative manufacturing, this study identifies four key attributes, summarised in Table 1, which provide a theoretical foundation for developing and assessing regenerative industrial practices. The first attribute, Integration with Natural Ecosystems (A1), proposes aligning industrial processes with ecological cycles, recognizing the environment as a living system to be restored and not just as a resource. This reconnection is achieved through practices such as biomimicry and ecological design. The second attribute, Circularity and Systemic Value (A2), extends the logic of the circular economy by considering multiple dimensions of value (environmental, social, and economic) through closed-loop production chains and products designed for reintegration from the outset. The third attribute, Social Justice and Production Ethics (A3), extends regeneration to the field of human relations, promoting inclusion, equity, and participation of local communities in value chains. Finally, Learning and Adaptability (A4) reinforces that regeneration requires collaborative innovation, openness to error, and organizational resilience, guided by values and a vision for the future.

Table 1. Attributes of regenerative manufacturing

| Attributes | Description | Ref. |
|---|---|---|
| Integration between Productive and Natural Ecosystems (A1) | Regenerative manufacturing proposes a reconnection between industry and nature, guiding its production processes by the principles of ecological systems. Instead of viewing the environment as a resource to be exploited, this approach recognizes it as a living system to be restored. It incorporates practices inspired by biomimicry and adopts models of ecological integration between production processes and natural dynamics. | [2], [5], [6] |
| Circularity and Systemic Value (A2) | It goes beyond the logic of "reduce, reuse, and recycle," promoting closed-loop production chains and business models based on continuous flows of materials and energy. Regenerative manufacturing incorporates systemic thinking, aiming to create value for multiple stakeholders (environmental, social, and economic), while designing products for ecological or technological reintegration from their conception (regenerative design). | [2], [3], [21] |
| Social Justice and Production Ethics (A3) | Regenerative manufacturing prioritizes principles of inclusion, equity, and social justice. This requires rethinking value chains to ensure decent working conditions, fair remuneration, diversity, and effective participation of local communities. | [2], [4], [6] |
| Learning and Adaptability (A4) | Regeneration requires a culture focused on continuous learning and collaborative innovation. Regenerative organizations cultivate skills to adapt to complex and constantly changing contexts, involving various stakeholders in cooperative processes. This approach strengthens organizational resilience, transforming mistakes into opportunities for improvement, while transformations are guided by regenerative values and a forward-looking vision. | [4], [6], [7], [8], [22] |

## 3. Methodological procedures

This study adopts a qualitative, exploratory, and descriptive research design. This methodological perspective allows for an in-depth understanding of the interactions between technological, social, cultural, and institutional factors[23], [24]. Qualitative research supports interpreting existing contributions from various sources, such as documents, discourses, and practices [25], [26].

This study uses the MLP to explore the concept of regenerative manufacturing [1], [2], [4]. As presented in Section 2.3, four structuring attributes of regenerative manufacturing were defined. To identify the four attributes, a search was conducted in Scopus and Web of Science using the terms "regenerative manufactur" and "sustainability." Articles were fully reviewed, with relevant references also examined to find additional studies. The attributes were drawn from interpreting these papers, merging common definitions to reach the proposed attributes. This exploratory approach reflects the early stage of regenerative manufacturing in academic literature, with triangulation across papers enhancing validity.

These attributes served as basis to construct a dynamic understanding of regenerative manufacturing, and a process model-based theorization [27] was adopted. This approach integrates the MLP [7] with regenerative manufacturing attributes. For the operationalization of the MLP levels, we defined explicit criteria: (i) landscape: macrostructural factors, such as national policies, environmental pressures, and socioeconomic trends; (ii) socio-technical regime: meso-level factors, such as norms, institutional structures, policy technologies, and organizational routines, and (iii) niche innovations: emerging practices, experiments, and innovative solutions.

To ensure a comprehensive view of regenerative manufacturing and sustainability transitions, a documentary research approach was employed. The unit of analysis was subsequently delineated. The selection of Brazil as a case study was predicated on its status as a nation in the Global South and its pertinence as a member of the BRICS (Brazil, Russia, India, China, and South Africa) economic alliance.

For this longitudinal study, we drew on official government repositories, legitimate non-profit organisation, and research institutions. Data was collected from Brazilian Brazilian organizations, such as an Agency from the Brazilian Ministry of Environment and Climate Change [30], the National Development Bank [31], the Ministry of Work and Employment [32]. Other international sources were also used, as is the case of documents published by the UNDP (United Nations Development Program) [33], and the World Bank [34]. These sources complemented academic publications with perspectives from policymakers and development agencies.

Table 2 outlines the indicators used for each regenerative manufacturing attribute. For A1 (Integration with Natural Ecosystems), land-use indicators regarding GEE emissions and deforestation seek to assess how production systems interact with ecological dynamics. A2 (Circularity and Systemic Value) uses waste generation to gauge circular practices, with lower waste indicating more closed-loop systems and reduced impact [21]. A3 (Social Justice and Production Ethics) employs industry financing and formal employment to reflect investment appetite and adherence to work legislation. A4 (Learning and Adaptability) is measured via human development index (HDI) and poverty, as minimum HDI and income levels are essential for educational access towards industry employment.

Table 2. Coding categories linked to regenerative manufacturing attributes

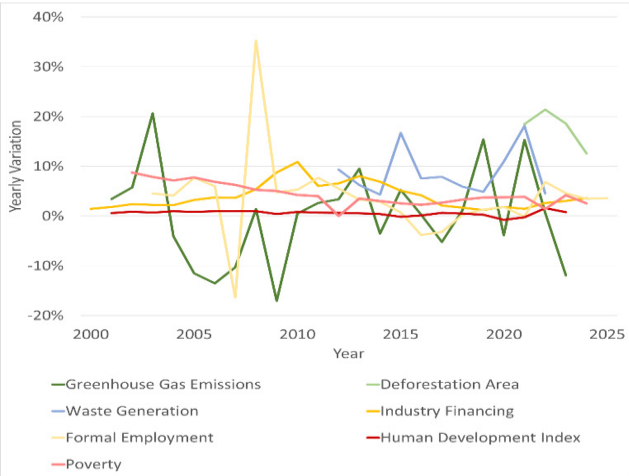
| Attributes | References |
|---|---|
| A1 | Greenhouse Gas Emissions [28]; Deforestation Area [29] |
| A2 | Waste Generation [30] |
| A3 | Industry Financing [31]; Formal Employment [32] |
| A4 | Human Development Index [33]; Poverty [34] |

Data were then structured into a timeline (2000–2025), Although regenerative manufacturing is a recent concept, the principles of regeneration have been applied in areas such as agriculture since 1970. Analysis of documents from 2000 to 2025 allows debate on the regenerative manufacturing attributes, even without the explicit use of the term. The selection of indicators followed three criteria: continuous availability of historical series, conceptual coherence with respective regenerative attribute, and relevance to the production context. This protocol ensured consistency, transparency, and rigor in the operationalization of the indicators. Enabling a longitudinal perspective on advances, setbacks, and gaps, this strategy connected conceptual attributes with Brazil's historical trajectory, offering insights into the potential to accelerate regenerative transitions.

## 4. Results

Fig. 1 shows collected the data in terms of annual percentage variation of indicates presented in Table 2, highlighting the rate of growth (or decline). It enables the comparison of variables even if they are in different measurement scales. Following, each regenerative attribute is analysed in further detail.

Fig. 1. Longitudinal Study (2000-2025)




### 4.1. Integration with Natural Ecosystems (A1)

Greenhouse gas (GHG) emissions in Brazil are closely linked to land use, especially deforestation. In 2003, there was a significant increase in emissions driven by the devastation of the Amazon, which reached 25,400 km² that year, one of the worst rates since 1988 [28]. In the following years, Brazil began to integrate international mitigation commitments, especially after COP-15 (2009), held in Copenhagen. The country assumed voluntary reduction targets, focusing on containing deforestation, adopting sustainable practices in agriculture, and increasing energy efficiency.

However, starting in 2013, there was a new increase in emissions, caused by the resumption of deforestation in the Amazon and Cerrado regions. From 2019 to 2022, deforestation continued experienced a period of growth showing a rise of 474,000 hectares deforested [29]. These patterns suggest that the pressure on ecosystem functioning is increasing, which weakens the conditions necessary for production ecological integration under A1. Therefore, land-use dynamics determine whether the materials that feed into manufacturing contribute to degradation or regeneration. Regenerative manufacturing is only possible when the extraction and production of inputs halt deforestation and improve ecological conditions, ensuring a net positive impact.

### 4.2. Circularity and Systemic Value (A2)

A considerable increase in the waste generation indicator is evident in Fig. 1 for the years 2020 and 2021. This increase has occurred in parallel with the Covid-19 pandemic, when changes in consumption patterns significantly impacted the profile of municipal solid waste in Brazil. Driven by the intensification of e-commerce, the growth in online shopping, motivated by social isolation, led to the massive use of packaging, resulting in a significant volume of cardboard, plastics, and other potentially recyclable waste [35]. However, this increase in recyclable waste has not been accompanied by a proportional increase in effective recycling rates, with part of the volume collected being sent to landfills or other forms of final disposal, instead of being processed and reinserted into production chains. Due to the critical period of the pandemic, many cooperatives of waste collection faced health restrictions and financial limitations, leading to a reduction in activities at sorting centres or even their closure, highlighting the fragility and low resilience of the selective collection infrastructure in crisis contexts [36].

In this way, we move from a linear production system to a truly regenerative system, in which we adopt circular methods from the outset, where packaging is redesigned to reduce waste generation at the source, materials continuously return to production cycles or industrial processes, promoting a net positive impact. This includes expanding resource systems, promoting efficient reverse logistics, and supply chains capable of restoring natural resources instead of depleting them.

### 4.3. Social Justice and Production Ethics (A3)

In 2007, the federal government presented a strategy to promote economic growth through major investments in social, urban, logistics, and energy infrastructure, the Growth Acceleration Program. The BNDES (National Bank for Economic and Social Development) was the main financing agent for these investments, disbursing large amounts of financing to industry[31]. However, starting in 2015, the country was hit by a serious political and economic crisis, aggravated by the presidential impeachment process and the progress of Operation Car Wash (one of the largest corruption cases ever investigated in the country), compromising the credibility of several companies financed by the BNDES [37], [38]. This led to a paralysis in important projects and weakened public credit in industry. Brazil entered a deep recession, with a cumulative decline in GDP and a significant increase in unemployment. As demonstrated in Fig. 1, the indicator of formal employment also exhibited a decline during the specified period.

In 2020, due to the emergence of the Covid-19 pandemic, the federal government launched emergency measures to mitigate the effects of the crisis. Among the programs created, the Emergency Credit Access Program (FGI-PEAC) stands out, instituted by Provisional Measure No. 975/2020 and converted into Law No. 14,042/2020[39]. Its objective was to expand access to credit for individual microentrepreneurs and micro, small, and medium-sized enterprises (MSMEs) by granting loans aimed at maintaining employment and income. The Emergency Employment Support Program (PESE) was also implemented, offering credit to companies to pay their payroll, limited to two minimum wages per employee. These programs contributed to the partial resumption of formal employment and industrial activity. The regenerative approach recognizes that productive systems cannot generate real positive impact simply by restoring ecosystems; it is also necessary to strengthen communities and promote decent working conditions. Thus, social justice and production ethics are inseparable dimensions of regeneration, since a system is only truly regenerative when it creates environmental, social, and economic value in an integrated way.

### *4.4. Learning and Adaptability (A4)*

The Human Development Index (HDI) in Brazil has fluctuated slightly in recent years. Notably, it fell in 2015 due to economic and political turmoil, and again in 2020 as the Covid-19 pandemic negatively impacted health, education, and income. While HDI does not directly measure organisational learning, its elements reflect societal conditions that influence the emergence of adaptive practices. Changes in HDI signal how favourable the environment is for developing Learning and Adaptability (A4). The country recorded a significant reduction of population living in extreme poverty (income below US$ 2.15 per day) from 2003 onwards, due to the implementation of the Bolsa Família Federal program, which promoted social inclusion and income transfer. In 2016, however, this progress was partially reversed due to the economic and political crises in the country. The level of poverty affects learning capacity, especially at young ages, due to the increased probability that children enter the labor force, leave school, or fail to advance in school [40]. More stable conditions tend to facilitate long-term investment in learning and skills development, while periods of increased vulnerability can signal constraints to the collective processes that support adaptability.

## 5. Discussion

Following, results are discussed in light of the Multi-Level Perspective (MLP).

### *5.1. Landscape*

At the landscape level, the results confirm that climate change and environmental pressures are key drivers of transformation. The increase in GEE emissions in 2003 and again in 2013 and 2019 is strongly associated with deforestation, highlighting predatory land use practices [28], [29]. This corroborates with previous indications [7] that sociotechnical regime practices (such as predatory land use) can directly affect the landscape level (in this case, in terms of GEE emissions impacts). Besides, this situation reinforces the analysis by Rockström et al. [41] on planetary boundaries and the urgency of reviewing practices towards regenerative models. In addition, the Covid-19 pandemic changed consumption patterns and increased waste generation but also revealed the fragility of recycling infrastructure and socioeconomic inequality [35], [36]. Events of this nature confirms Schot and Geels'[8] perspective that landscape pressures create windows of opportunity for change, even if they are not always exploited in a structural way.

### *5.2. Socio-technical regime*

This study indicates that the described landscape, composed of the dichotomy between low level of environmental concerns with global impact of high biodiversity embedded in the Amazon forest and other Brazilian biomes, tends to affect the country´s sociotechnical regime. The Brazilian regime shows signs of institutional inertia. In 2007, we had the Growth Acceleration Program (PAC), which prioritized investments in infrastructure, reinforcing conventional industrial standards centred on extractivism [37], [38]. This production system logic is not aligned with regenerative principles, echoing Meadows et al.'s [42] criticism of the unlimited growth model. Starting in 2015, political and economic crises weakened the regime, but instead of opening space for changes towards regenerative manufacturing initiatives, they caused recession, unemployment, and a decline in industrial investments. In this context, an increase in extreme poverty and a reduction in the HDI were observed, highlighting the fragility of the social dimension [33]. This reinforces the analysis by [15] on the difficulty of transforming established regimes, as they tend to protect their structures even in the face of crises. This evidences reinforces traditional sustainability perspective on the intrinsic relation between economic, environmental, and social goals.

### *5.3. Niche innovations*

Despite the predominance of conventional practices, the results show the emergence of innovation niches aligned with regenerative manufacturing. Initiatives in regenerative agriculture, circular economy, and integration of digital technologies point to paths toward more sustainable chains [1], [2]). However, as demonstrated by the pandemic experience, these niches still lack institutional support. The increase in the collection of recyclables without a corresponding growth in recycling shown by the empirical evidence presented in this study reinforces the analysis by Kemp, Schot, and Hoogma [43] on the vulnerability of innovations when not supported by robust protection and incentive policies.

In summary, the analysed Brazilian longitudinal data showed that their incorporation is still incipient. Therefore, the regenerative transition in Brazil can be seen as an ongoing but still slow process. It is in line with Geels' [44] argument that socio-technical changes do not occur abruptly, but in a complex manner. Advancing this process requires strengthening niches, aligning institutions through structural public policies and markets toward regenerative values, and creating conditions for external pressures to be converted into opportunities for transformation. One way to support sustainability transition towards regenerative manufacturing is to develop further indicators and measures for each attribute, exploring their interplay with the three levels of the MLP.

## 6. Conclusion

The shift from sustainable to regenerative production remains a technical, institutional, and cultural challenge. This study advances the debate by identifying four key attributes of regenerative manufacturing: integration with natural ecosystems, circularity and systemic value, social justice and production ethics, and the capacity for learning and adaptation. These form a framework for assessing new industrial practices. Historical analysis of Brazil shows that a linear, environmentally degrading regime still dominates. Study's limitations include the reliance on secondary data and low number of variables considered for each attribute. Future research can deepen case studies, develop its own regenerative production indicators, and compare different national contexts. Thus, this research broadens our understanding of the conditions and challenges of a regenerative industrial transition in Brazil.

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