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A MULTIMETHODOLOGICAL APPROACH TO ORGAN DONATION LOGISTICS: SYSTEMIC ANALYSIS OF BRAZILIAN FEDERAL UNITS THROUGH QUALITATIVE SYSTEM DYNAMICS AND EFFICIENCY ASSESSMENT USING DATA ENVELOPMENT ANALYSIS

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ABSTRACT. Organ transplantation plays a significant role in the healthcare sector, offering hope to patients with chronic diseases and organ failure. However, the logistical aspects of organ transplants present significant hurdles, with inefficiencies leading to organ loss during transportation and fatalities while on the waiting list. In this study, the combined use of Qualitative System Dynamics and Data Envelopment Analysis is employed to investigate, map, and analyze the efficiency of organ transplant logistics across different Brazilian Federative Units. From the Causal Loop Diagram, five (three as inputs and two as outputs) variables were selected to assess the efficiency through an output-oriented Data Envelopment Analysis model considering constant returns to scale. The results highlight efficient/inefficient Units, offering benchmarks and targets for improvement. This integration of methodologies provides a comprehensive perspective, empowering informed and strategic decision-making in the development of effective public policies and optimal allocation of public resources, thereby enhancing precision and efficiency.

Keywords: system dynamics, data envelopment analysis, organ transplants.

1 INTRODUCTION

Organ transplantation is frequently the sole and judicious recourse for treating certain ailments that are deemed terminal, thereby ensuring the enhanced quality of life for patients

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(ABTO, 2020). It is an altruistic endeavor that possesses the potential to rescue lives and serve as a catalyst for a new beginning for individuals who are in dire need of donations (Brasil, 2021). Brazil currently holds the second position worldwide in terms of the total number of transplants performed, second only to the United States (Brasil, 2022). Notably, approximately 96% of all donations are supported by the Government through the Unified Health System (SUS), encompassing preoperative examinations, post-transplant surgeries, and medications (Brasil, 2021). In 2020 alone, the Ministry of Health invested approximately BRL 1.6 billion in transplant procedures (Brasil, 2021).

However, the advent of the Covid-19 pandemic disrupted the projected trajectory, which aimed to achieve a transplant rate of 20 procedures per million people (pmp) in 2020 (Brasil, 2022). Instead, the rate declined to 15.8 pmp, equivalent to the rate observed in the first half of 2017. The Brazilian Transplant Registry (RBT) (ABTO, 2022), released in the first half of 2022, identifies two primary factors contributing to this reduction. Firstly, there is a strain on intensive care units (ICUs) caused by overcrowding and excessive workload. Secondly, the National Transplant System (SNT) advised against transplantation due to the potential risk of coronavirus transmission (ABTO, 2022).

According to data from 2021, there are nearly 55,000 individuals awaiting contact from public institutions, notifying them that their surgery is imminent. However, not all of them will receive assistance, particularly those residing far from major urban centers (Brasil, 2021). Historically, kidney transplantation has been the most sought-after procedure, with approximately 25,000 patients in the queue. Shockingly, in 2019, only 6,283 kidney transplants were performed, meeting just 25% of the demand (ABTO, 2020). In Brazil, 67% of transplant units are concentrated in megalopolises located in the South and Southeast regions, where the majority of surgeries take place (Gómez et al., 2018). Nonetheless, the mere availability of more resources does not guarantee a proportional increase in the number of successful transplants, no matter how much they are promoted. Hence, it is evident that, apart from the challenges of geographical distances and limited access for the population, transplants may not be fully realized due to logistical inefficiencies.

The absence of a well-structured, efficient, and effective logistical system is one of the many factors contributing to organ losses in transplantation. Even minor enhancements in the entire process, starting from a patient's inclusion on the waiting list to the postoperative phase, can significantly enhance the efficacy of transplants and save lives (Andrioli, 2015).

Regrettably, the current organ transplantation method continues to grapple with numerous systemic issues that necessitate a more in-depth analysis (Pullen, 2019). These challenges are inherent to the practice and include factors such as ischemia time (the duration an organ can survive without blood circulation), adequate storage during transportation, and the proficiency of the surgical team. Compounding the problem is the fact that each Federative Unit in Brazil is responsible for managing the organ transplant program (Brasil, 2021), leading to an uneven distribution of resources across the country. This disparity includes the availability of transplant-ready hospitals, qualified medical teams, and other essential components. Given the complexity of this subject and the multitude of variables involved, it becomes imperative, from a public policy standpoint, to examine which Federative Units demonstrate greater efficiency in utilizing public resources allocated to transplant-related activities.

Given the significance of the logistical aspect in the organ transplantation process, this paper focuses specifically on investigating, mapping, and analyzing the efficiency of organ transplant logistics across the various Brazilian Federative Units. To achieve this objective, the research utilizes a multimethodological approach, aggregating the Causal Loop Diagram, as proposed by Forrester (1951) and Data Envelopment Analysis (DEA), originally introduced by Charnes et al. in 1978.

The selection of these methods was driven by their broad applicability. On one hand, System Dynamics, with its Causal Diagram tool, has been successfully employed in various domains, including education, sustainability, public and business administration, and healthcare, among others (Hill & Camacho, 2017; Sterman et al., 2015; Strauss & Borenstein, 2015; Morecroft, 2015). On the other hand, DEA is highly adaptable for evaluating the efficiency of decision-making units (DMUs) by considering input variables (resources) and output variables (products) simultaneously. Moreover, DEA facilitates the identification of best practices and sets targets for inefficient DMUs, using linear mathematical programming techniques (Soares de Mello et al., 2005). This flexibility has expanded the application possibilities of DEA in the healthcare sector (Mariano et al., 2021, among others).

This manuscript is organized as follows: in the next section, Section 2, the Theoretical Background for both the Causal Loop Diagram and Data Envelopment Analysis is presented. Moreover, this section includes a review of literature involving application in the organ transplant process system. In section 3, the case study is presented, in which the Organ Donation in Brazil is presented, as well as, the logistical aspects of organ transplantation of the Brazilian service. Section 4 presents the results, that is, the causal loop diagram of Brazilian Organ Donation Logistics and then the results of the efficiency assessment using DEA. Also, in this section, the results are discussed. Finally, in Section 5, the conclusions of this study are presented.

2 THEORETICAL BACKGROUND

2.1 Causal Loop Diagram

Healthcare systems exhibit a noteworthy complexity, constituting adaptive structures replete with interconnected entities, the interactions among which orchestrate the overall system's behavior, as elucidated by Plsek and Greenhalgh in 2001, Braithwaite et al. in 2017, and Braithwaite et al. in 2018. To gain insight into and intercede within such intricate frameworks, numerous methodologies have been embraced. Examples include the application of Problem Structuring Methods, exemplified by Strategic Option and Development Analysis (SODA), complemented by its cognitive SODA maps, as expounded by Rosenhead and Mingers in 2001 and further advanced by Rosenhead in 2006. Additionally, Soft System Methodology (SSM), as introduced by Checkland in 1981 and further discussed by Reisman and Oral in 2005, along with Augustsson et al. in 2020, has been instrumental in providing a lens through which to comprehend these intricate systems.

Traditionally, the prevailing approach has encompassed the utilization of System Dynamics (SD), Agent-Based Modeling, and Discrete Event Simulation, as notably advocated by Zhang et al. in 2023 and Breeze et al. in 2023. This approach has ushered in advanced analytical techniques that involve the incorporation of complex system models. In the context of our current endeavor, we are focused on unraveling the intricate web of relationships among the variables that constitute the logistical framework for organ donation in Brazil. To this end, we have elected to employ the Causal Loop Diagram as the most suitable tool for representing the feedback loops inherent in this system.

System dynamics, initially developed in the 1950s, serves as a modeling and simulation tool for analyzing complex systems. Its development can be credited to Jay Forrester, a professor at the Massachusetts Institute of Technology (MIT). Forrester drew upon various elements, including computational simulation, information-feedback system theory, the experimental model approach for complex systems, and an understanding of decision-making processes, to establish this theoretical field (Collins et al., 2013; Forrester, 1958; Sterman, 2000).

The primary objective of system dynamics is to capture the dynamic trends of an entire system, rather than focusing solely on specific moments or individual variables (Dos Santos, 2006). By employing computational models, system dynamics allows for a holistic representation of the system, accounting for interdependencies and feedback loops among various components. This approach enables the exploration and understanding of system behavior over time, facilitating insights into the underlying mechanisms and dynamic patterns that drive the system's behavior.

Causal diagrams, also known as causal loop diagrams, and stock and flow diagrams are key elements in system dynamics. Causal diagrams provide a qualitative understanding of the system by visually representing the interactions between events. On the other hand, stock and flow diagrams aim to quantitatively analyze the behavior of the system. To facilitate analysis, equations can be developed to represent the dynamics of stocks and flows, which can then be incorporated into simulation software (Strauss & Borenstein, 2015).

The construction of a causal diagram is a crucial step in developing a system dynamics model. It serves as a visual representation of the system, illustrating its components and their respective interactions (Haghshenas et al. 2015). This diagram depicts cause-and-effect relationships among variables and identifies the feedback loops associated with each relationship. Feedback loops are represented graphically using arrows or links, with indications of polarity (positive or negative) and loops, along with descriptive information (Morecroft, 2015).

Causal relationships within a causal diagram are represented by arrows, which can have positive or negative polarity, as depicted in Figure 1. These arrows indicate the cause-and-effect relationship between the corresponding events. When determining the polarity of a relationship, only the two variables connected by the link are considered, while the other variables are treated as constants (Amaral, 2012; Sterman, 2000).

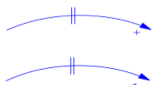
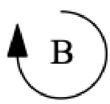
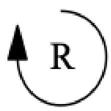
Elements	Meaning
	**Positive causal relationship.** If the cause increases, the effect increases above what would otherwise have been.
	**Negative causal relationship.** If the cause increases, the effect decreases bellow what would otherwise have been.
	**Causal relationship with delay.**
	**Balancing feedback loop.**
	**Reinforcing feedback loop.**

Figure 1 – Causal Loop Diagram (CLD) elements.

A positive causal relationship signifies that the cause and effect are directly proportional. In other words, an increase in the cause leads to an increase in the effect, and vice versa. On the other hand, a negative causal relationship indicates an inverse proportionality between the cause and effect. In this case, an increase in the cause results in a decrease in the effect, and vice versa (Amaral, 2012; Morecroft, 2015).

2.2 System Dynamics and Organ Transplantation

The Scopus database was used for the research of the academic works. Initially, materials related to the three explored themes (system dynamics, transplantation, and logistics) were searched using the terms "system dynamics," "logistics," and "transplant" in the title, abstract, or keywords, without filters regarding the type, period, or authorship of the publications. However, no results were found with these specifications. All searches were conducted in March 2021.

Next, these themes were searched in pairs, with the search of the themes system dynamics and transplantation; system dynamics and logistics; and transplantation and logistics, using the terms "system dynamics" and "logistic," "system dynamics" and "transplant," and "transplant" and "logistic" in the title, abstract, or keywords. Once again, there were no filters regarding the type, period, or authorship of the publications. Table 1 provides a detailed summary of the searches conducted and the total number of results for each of them.

Table 1 – Research summary.

Search	Keywords/Searched Terms	Type	Results
1	1) "System Dynamics" 2) Transplant 3) Logistic	Title-abstract-keywords	0
2	1) "System Dynamics" 2) Transplant	Title-abstract-keywords	5
3	1) "System Dynamics" 2) Logistic	Title-abstract-keywords	550
4	1) Transplant 2) Logistic	Title	23

The objective of the Search 2 was to select papers that presented a general model of organ transplantation for a better understanding of the process and analyzed variables, as well as identifying considerations about the logistics of the system. Firstly, the availability of the full paper was checked, but all five papers found in the search were available in full. Subsequently, an initial analysis was conducted by reading the abstract and keywords solely for the purpose of understanding the context, without applying any filters at this stage. Next, it was necessary to verify if the paper included a System Dynamics (SD) model, such as a concept map and/or stock and flow diagram for analysis. Only one out of the five papers did not have a model and was excluded at this stage. Finally, a more detailed analysis of the content of the selected papers was carried out, understanding the scope of the constructed models and the information related to the logistics of organ transplantation addressed in the papers. Articles that did not present variables that could be adapted to the model to be developed in this work were discarded. In this case, two more articles were excluded: one because it focused on a model that aimed to use system dynamics to predict the population with end-stage renal disease, addressing the disease that leads to the need for transplantation but not providing details about the transplantation itself; and the second because it was an example discussed in a book chapter. After this stage, the remaining two articles were selected. Lastly, an additional search was conducted in the references of the selected papers and in Google Scholar, following the previous criteria, adding two more papers to the selection, resulting in a total of four articles for analysis, as presented in this section.

Although Search 3 and Search 4 are not explicitly presented in this work, their results were utilized as inputs for variable selection in Subsystem 2 and Subsystem 3, as depicted in the Causal Loop Diagram (CLD) in the Results subsection 4.1. The four articles selected with the themes system dynamics and logistics, with the research and criteria described are presented in Table 2 and discussed in this section (Cruz et al., 2019; Devi et al., 2010; Hirsch et al., 2012; Paricio & Figal, 2015).

The article by Devi et al. (2010) investigates policies aimed at reducing the waiting list and waiting time for corneal transplants in India. The study utilizes system dynamics methodology, starting with the development of a causal diagram, model equations, and ultimately, a simulation of the waiting list over a period of 48 months. Although the focus is on corneal transplantation, the authors suggest that the model can be applied to the transplantation system of other organs as well. The research specifically concentrates on modeling the waiting list and addressing the imbalance between organ supply and demand.

Table 2 – Selected papers: System Dynamics and Organ Transplantation.

Title	Year	Authors	Source
System dynamics model for simulation of the dynamics of corneal transplants	2010	Devi SP, Rao KS, Krishnaswamy S, Wang S.	Devi et al. (2010)
Deceased Donor Potential for Organ Transplantation: A System Dynamics Framework	2012	Hirsch G, Saeed K, McCleary K, Myer K.	Hirsch et al. (2012)
A System Dynamics Model of the Kidney Transplants in the U.S.	2015	Paricio I, Figal J.	Paricio & Figal (2015)
Kidney procurement system in Colombia: A system dynamics approach	2019	Cruz JP, Guerrero WJ, Pérez ER, Lizarazo DL, Rico PC, Castillo AM, Torres LN	Cruz et al. (2019)

The Organ Procurement and Transplantation Network (OPTN) commissioned and funded the research conducted by Hirsch et al. (2012) with the objective of gaining a comprehensive understanding of the transplant system's functioning, estimating the number of potential deceased donors, and evaluating strategic policies to increase organ supply. The researchers developed a model divided into subsystems, drawing on the input, opinions, and validation of system operators, subject matter experts, and visits to Organ Procurement Organizations (OPOs). The resulting article presents a general model of the transplantation process, albeit without a specific focus on logistical aspects.

Paricio & Figal (2015) conducted a study focusing on kidney transplantation in the United States. The research addressed several challenges associated with this field, including the significant increase in the waiting list, the high mortality rate among patients waiting for a transplant, the loss of kidneys due to a lack of organ donors at the time of death for over half of the population, difficulties in raising public awareness, disparities in the distribution of the problem based on blood type, and the ethical and moral considerations surrounding donation promotion. The objective of the study was to utilize a system dynamics model to analyze the current state of kidney transplantation in the country and simulate the effects of implementing various policies to gain a deeper understanding of their impact.

The study conducted by Cruz et al. (2019) aims to comprehensively analyze two potential policies to address the existing imbalance between the number of kidney donors and the extensive waiting list for this organ in Colombia. To accomplish this, the researchers meticulously construct a sophisticated causal diagram of the system, accompanied by a corresponding stock and flow model. Through rigorous simulations, they strive to gain profound insights into the quantitative aspects of diverse scenarios. The primary focus of the intricately developed model lies in accurately diagnosing and understanding the prevalence of chronic kidney disease (CKD), particularly in its advanced stages (stage 5), where a kidney transplant becomes imperative for effective patient treatment. The model encompasses crucial factors such as the list of individuals diagnosed with CKD, the waiting list for kidney transplants, and the actual occurrences of successful transplantations. Consequently, the comprehensive causal diagram is thoughtfully segmented into three distinct subsystems, namely CKD diagnosis, the waiting list, and kidney donation.

In terms of the articles' general aspects, it is notable that two of them focus on the United States, while the other two concentrate on Colombia and India, highlighting the diversity of geographical contexts considered in the studies. Additionally, three out of the four articles specifically investigate kidney transplantation, which reflects the high demand and activity associated with this organ. According to the Global Observatory on Donation and Transplantation (GODT, 2021), kidneys accounted for 65% of the total transplants performed worldwide in 2019, further underscoring their significance.

All the reviewed articles incorporate causal diagrams as a fundamental component of their models. However, there are variations in the completeness and structure of these diagrams. Some articles present a comprehensive causal diagram, encompassing all relevant variables in a single diagram, while others adopt a segmented approach with multiple diagrams that lack an overall view of all variables.

In terms of the stock and flow diagrams and subsystem division within the models, there are variations among the articles. Devi et al. (2010) does not include a stock and flow diagram or explicit subsystem division in their model, while Hirsch et al. (2012) employ separate stock and flow diagrams for each subsystem, totaling nine diagrams. It is worth noting that all articles employ simulations with real data and propose policy recommendations. However, Devi et al. (2010) solely presents these proposals in the conclusion without conducting simulations of the proposed scenarios, unlike the other articles.

To summarize the key characteristics of the articles, Table 3 provides a concise overview of the general data from each study.

Table 3 – Key Characteristics of Reviewed Papers.

	Devi et al. (2010)	Hirsch et al. (2012)	Paricio & Figal (2015)	Cruz et al. (2019)
Country	India	US	US	Colombia
Organ/Tissue donated	Cornea	Kidney	Kidney	Kidney
Causal Loop Diagram	Yes, completed	Yes, uncompleted	Yes, uncompleted	Yes, completed
Stock and Flow Diagram	No	Yes, uncompleted	Yes, completed	Yes, completed
Model and Subsystems?		X	X	X
Equations?	X			
Simulation with real data?	X	X	X	X
Policies proposals?	X	X	X	X
Policies simulations?		X	X	X

The sources used to construct the models are summarized in Table *4*. Overall, Devi et al. (2010) and Paricio & Figal (2015) conducted tests, including simulations under extreme conditions. Cruz et al. (2019) relied on expert interviews, input from system operators, and a thorough literature review. Hirsch et al. (2012) had a more diverse range of sources for structuring their model, incorporating input and validation from specialists and operators. They also conducted visits to Organ Procurement Organizations (OPOs) and performed tests, such as comparing historical data with model simulations for the same period.

The transplant logistics variables identified in the articles encompass various aspects of the process. Starting from the number of donors, variables such as potential donors, percentage of donation, and donations made were consistently addressed in all the articles. The outcomes of successful transplants, unsuccessful transplants, and their potential impact on the waiting list were also key variables examined in all the studies. Furthermore, some articles delved into variables related to donation and public awareness campaigns.

In addition to the variables at the beginning and end of the process, intermediate variables were identified that pertain to the logistics of organ donation. These include the allocation process, which involves factors such as crossmatch and success rates, acceptance rates, and allocation for urgent cases. Other variables encompassed the transport of organs, graft quality indicated by organ damage rates and organ quality, as well as system capacities such as hospital capacity, capacity required per transplant, and the resources of demand organizations.

While the articles may not have provided extensive details or focused solely on the logistical aspect of the process, the variables compiled in Table 5 are vital for understanding and managing the logistics of the transplantation process.

Devi et al. (2010) identified the scarcity of resources as a significant factor contributing to the unmet demand for transplants. They highlight the insufficiency of resources, which includes facilities, equipment, and personnel, as a constraint in meeting the transplant needs. Additionally, the authors underscore the absence of effective organ tracking systems and demand organizations as additional challenges in the transplantation process. These deficiencies lead to inefficiencies, such as wastage of organs and the risk of infections, and contribute to delays due to the need

Table 4 – Data sources of System dynamics Models.

	Devi et al (2010)	Hirsch et al (2012)	Paricio & Figal (2015)	Cruz et al. (2019)
Experts interviews		X		X
Health operators interviews		X		X
Experts validation		X		
Health operators validation		X		
Literature Review				X
Technical visit to health organizations		X		
Tests performed	X	X	X	

to coordinate operating rooms and the lack of proper coordination among the human resources involved in the process. These factors collectively hinder the smooth functioning of the transplant logistics and contribute to the inability to meet the demand for organ transplantation effectively.

Hirsch et al. (2012) also emphasize the significance of organ quality in the transplantation process, as it plays a crucial role in determining the success of transplants. The quality of the organ influences various factors, including the risk tolerance of surgeons and the willingness of patients to join the transplant waiting list. The authors argue that the average organ quality is directly influenced by the acceptance criteria set by transplant programs. Accepting organs with suboptimal conditions allows more patients on the waiting list to receive transplants, thereby reducing waiting times. However, accepting lower quality organs can also increase the risk of graft failure and mortality among transplant recipients. It is worth noting that in the case of kidneys, the retrieval of available organs is relatively efficient, with a lower occurrence of discarded organs. Most recovered kidneys are utilized for transplantation, while the remaining organs are either discarded or utilized for research purposes. The consideration of organ quality is therefore critical in balancing the trade-off between increasing transplantation rates and ensuring positive patient outcomes.

The article also discusses the organ allocation process and the role of matchmaking in transplantation. The acceptance criteria used in the allocation process have a direct impact on the number of organs that are recovered and subsequently facilitate faster matches between donors and recipients. The efficient allocation process and prompt removal and implantation of organs contribute to ensuring better graft quality. Additionally, the authors note that a larger pool of individuals on the waiting list increases the probability of finding compatible matches for the available organs, leading to a reduction in the number of discarded grafts. The consideration of allocation strategies and the management of the waiting list are crucial factors in maximizing the utilization of donated organs and minimizing wastage.

In Table 6 we provided a summary of the logistical considerations discussed in the four analyzed articles.

Table 5 – Variables (From Selected Papers).

	Devi et al. (2010)	Hirsch et al. (2012)	Paricio & Figal (2015)	Cruz et al. (2019)
Number of variables	25	~ 180	> 160	22
Variables includes in the model that are related to Logistics	11	12	11	5
Variable related to Potential Donors	Potential donors	Medically suitable donors	Potential available kidneys (teenagers, adults and elderly)	Potential donors
Variable related to Donation rate	Donation fraction	Donation rate		
Variable related to Campaigns	Campaign effectiveness			Awareness campaigns
Variable related to population awareness			-Awareness due to close friends/family transplants -Awareness due to media campaign	
Variable related to Donations	Donations	Organs for transplant	Total available kidneys	
Variable related to successful transplants	Sucessful transplants	Sucessful transplants	Sucessful transplants	Transplanted patients
Variable related to unsuccessful transplants	Unsucessful transplants	Graft failure	Bad acceptance of the organ	Patients rejecting kidney transplanted
Variable related to Waiting Lists	Waiting list	Active waiting list	Waiting list for a kidney transplant	Transplant Waiting List
Variable related to Crossmatch and success rate	crossmatching and sucess rate			
Variable related to transportation	Sent to other hospitals			
Variable related to organ outdating rate	Rate of outdation			
Variable related to organ/tissue quality	Outdated cornea	Organ quality		
Variable related to organ/tissue acceptance rate		Acceptance rate		
Variable related to hospital capacity		Transplant center capacity		
Variable related to hospital capacity per transplant		Capacity needed per transplant		
Variable related to resources of organizations which look for organs/tissues		OPO staff; OPO financial resources		
Variable related to priority policies			Kidneys from allocations priority policy going to transplantation	

Table 6 – Logistics aspects from Selected Papers.

	Devi et al. (2010)	Hirsch et al. (2012)	Paricio & Figal (2015)	Cruz et al. (2019)
Resources restrictions	X			X
Lack of tracking and search organizations	X			
Organ waste or damage	X	X	X	
Delays (from organ collection to the transplant)	X			
Transplant program's capacity		X		
Organ/Tissue allocation (donor - recipient)		X	X	

Furthermore, Hirsch et al. (2012) emphasize that the transplant rate and waiting time are not solely determined by the availability of donors and recipients, but also by the capacity of transplant programs. The efficiency and resources of these programs play a crucial role in determining the success of transplantation.

Similarly, Paricio & Figal (2015) address the challenge of organ loss in their study. Their model assumes that only 85% of available kidneys are utilized for transplantation, while the remaining 15% are lost, based on data from the Organ Procurement and Transplantation Network (OPTN). These losses can be attributed to difficulties in finding compatible recipients within a limited geographic area. The authors propose future research to investigate the impact of geographic differences within the country on the allocation and transport of donated organs. They suggest that integrating interstate collaboration would be essential to optimize the distribution of organs.

Lastly, Cruz et al. (2019) highlight that there are additional variables that affect the number of cadaveric kidney donors in the kidney donation subsystem. These factors include underdetection of potential donors, challenges in diagnosing brain death, failures in maintaining hemodynamic stability, and administrative and/or legal barriers such as resource unavailability for organ retrieval, which is particularly prevalent in Colombia, accounting for approximately 9.7% of cases.

2.3 Data Envelopment Analysis

Data Envelopment Analysis (DEA) (Charnes et al., 1978) is a linear programming-based technique for assessing the relative efficiency of a set of units known as Decision Making Units (DMUs), which considers multiple resources and products, called inputs and outputs, respectively. The fact that it does not require prior information about the importance of variables makes this methodology attractive, as it not only determines the efficiency index but also sets targets (efficient levels for inputs and outputs) for inefficient DMUs and identifies benchmarks with efficient managerial and/or operational practices.

In a DEA study, some methodological aspects must be considered, such as returns to scale, orientation, DEA model selection and definition of variables (inputs and outputs). Considering the returns to scale, it refers to the quantitative change of outputs due to the change in the amount of inputs, in this sense, one should determine in which scale the DMUs operate, being constant or variable the most frequent. In constant returns to scale (CRS), DMUs are said to be operating at the optimum scale, disregarding size or scale. Also, an increase in inputs produces a proportional increase in outputs and this proportion is constant. However, in many instances where the number of DMUs is small compared to the number of variables, CRS is assumed. If these conditions do not exist, a variable returns to scale (VRS) is assumed.

Moreover, the DEA model should clearly identify a way to become efficient; this is called the orientation of the model. The two most common are: to inputs, where the focus is on reducing the input levels while maintaining the output levels; and to outputs, where the focus is on increasing output levels while maintaining the input levels. The orientation depends on the priorities or limitations of the study.

The model used in this study is the output oriented CCR model (Charnes et al., 1978) presented in (1) that assumes constant returns to scale.

$$\begin{aligned}
&\text{Max } \varphi_o \\
&\text{subject to} \\
&\sum_j x_{ij}\lambda_j \leq x_{io}, \ \forall i \\
&\sum_j y_{rj}\lambda_j \geq \varphi_o y_{ro}, \ \forall r \\
&\lambda_j \geq 0, \ \forall j \\
&\varphi_o \in \mathbb{R}
\end{aligned} \tag{1}$$

Where ϕ_o is the proportional output increase, so the efficiency of DMU_o is $1/\phi_o$, λ_j is the contribution intensity of benchmark j to the target of DMU_o, x_{ij} is the input i of DMU j, and y_{rj} is the output r of DMU j. For other models and theoretical background on DEA refer to Cooper et al. (1997).

Regarding, the variables in a DEA assessment, their definition depends on the study and they must be selected ensuring that they properly reflect the process under study (Cook et al., 2014). Consequently, this is one of the most important aspects of a DEA study. In this study, a Causal Loop Diagram will be used to select the variables.

Also, variables are classified into inputs and outputs; the inputs being resources to be minimize, and the outputs, products to be maximize. However, there are instances where variables behave differently, outputs that are called undesirable outputs or even bad outputs. This can also occur for inputs. These variables are known in DEA literature as undesirable outputs and require different treatment. In DEA literature, there are different approaches to deal with such variables (Scheel, 2001). In this manuscript, we propose dealing with undesirable outputs using them as inputs, in this way, the variable would turn into a variable to be minimize.

On the other hand, due to the benevolent nature of the DEA assessment, where several DMUs may efficient, or even to obtain a ranking of DMUs, one can choose among several DEA methods (Angulo-Meza et al, 2002). One of these is the Inverted Frontier (Leta et al, 2005; Soares de Mello et al., 2008). The inverted frontier concept consists of considering outputs as inputs and inputs as outputs, that is, variables swap. The variable swap identifies DMUs with the worst managerial practices, and it can thus be called an inefficient frontier. This is because, for inputs, we want to use the minimal amount possible to achieve a certain level of output. As for outputs, we want to produce the maximum amount possible when using a certain level of inputs. In swapping variables to find the inverted frontier, those who initially had a high level of inputs and those with low levels of outputs will be identified as efficient, or with high efficiency indexes. With the inverted efficiency index, the composed efficiency index can be calculated as in (2).

$$Eff_{compost} = \frac{Eff_{st} + (1 - Eff_i)}{2} \tag{2}$$

It is easy to see that Equation (2) is the arithmetic average between the efficiency considering the classic standard frontier, Eff_{st} (obtained by any DEA model before variable swapping) and the inefficiency (1 minus efficiency) considering the inverted frontier, Eff_i (with the same DEA model, after variable swapping). This index can be presented in a normalized form by dividing all efficiency scores by the biggest calculated score in a way that the efficiency indexes are between 0 and 100%. In this way, we obtain a composed efficiency index ranging from 0 to 1 and we use it to determine a ranking of DMUs. Also, the best ranked DMU has a mixture of good performance in the standard frontier (expressed through the standard efficiency index, low levels of inputs and high level of outputs) and "poor" performance in the inverted frontier (expressed through the inverted efficiency index). That is, this DMUs cannot be achieved the top rank by performing well in some variables and performing poorly in others, which may happen in classic DEA.

2.4 DEA and organ transplantation

As mentioned previously, Data Envelopment Analysis has been used to assess efficiency in many sectors especially in health or health related organizations. A review conducted by Liu et al. (2013a, 2013b) in the SCOPUS database and JCR publications, showed that these publications included organ transplantation related problems. However, as noted by Ahmadvand and Pishvaee (2018) and emphasized by Santos Arteaga et al. (2021), there is a lack of DEA studies applied to transplantation processes. It also worth noticing that research published in recent years has focused on the effects of COVID-19 in the organ transplantation process, such is the case of Revuelta et al. (2021) that proposed a hybrid data envelopment analysis—artificial neural network prediction model for COVID-19 severity in transplant recipients, which does not directly assess the efficiency of the organ transplantation process. Also, Manoel et al. (2023), that used DEA and the Malquist index to assess the impact that the pandemic caused by the novel coronavirus

SARS-CoV-2 had on the provision of solid organ transplant services; among other researchers that evaluate the consequences of the pandemic.

Concerning the efficiency assessment of the transplantation process using DEA, in the United States, Ozcan et al. (1999) assessed the efficiency of part of the transplantation process, the organ procurement organizations (OPOs) using DEA. The study focused on the recovering of kidneys and extrarenal organs, moreover they identified the benchmarks (efficient OPOs) characteristics in the use of resources and hospital personnel profile and those who are more likely to benefit from technical assistance. Later, Ahmadvand and Pishvaee (2018) applied DEA to evaluate the efficiency of potential (kidney) patient-organ allocation pairs while considering the uncertainty inherent to some of the variables. They used fuzzy numbers and implemented the principles of chance constrained DEA within a credibility-based Fuzzy Common Weights setting. To verify and validate their proposed approach they used data from the Iranian kidney allocation system. More recently, Santos Arteaga et al. (2021) classified a set of patients in terms of the efficiency of the transplantation process through three different phases of the transplantation process: pre-transplant, transplant and post-transplant, each composed by specific as well as interrelated variables. They used data from living donor kidney transplant patients through the 2006–2015 period in a hospital in Spain. Moreover, the study allowed the authors to identify the specific characteristics of patients which potential improvements could be defined on a per patient basis.

In Brazil, the first study using DEA in the transplantation processes was performed by Marinho et al. (2011) who evaluated the technical efficiency of the organs and tissues transplantation using DEA models identifying efficient states. They use data available from Health Ministry database to evaluate the Brazilian UFs corresponding to 2006. Results showed that there were disparities between States in which States in the South, Southeast, and Midwest regions had the highest transplantation and productivity rates and the largest per capita transplantation teams. More recently, Costa et al. (2014) used DEA and a Malmquist approach models to evaluate the efficiency in the public kidney transplant system and their productivity trends from 2006 to 2011. Their results suggest that the Institutional changes promoted by the Brazilian Ministry of Health (procedures improvement and standardization) may have failed to increase productivity in most States during the period of the study. Later, Siqueira and Araujo (2018), also focusing in kidney transplantation, used DEA to assess the efficiency of the Brazilian public services in transforming physical and labor inputs into kidney transplants. They also use the Malmquist index to evaluate performance among the years of 2013, 2014 and 2015, the results suggest a persistent inefficiency and lack of improvement over the years in the services that may be due to managerial shortcomings. Whereas, Marinho & Araújo (2021) focused on assessing the efficiency of the Brazilian states and the Federal District in transforming potential organ donors into actual donations. To do this, they used DEA with the bootstrap technique, using organ transplantation data from 2018, their study is not disaggregated by organ type, as donors may donate multiple organs and the focus of their study is on notifications (potential donors) and donors whose organs were transplanted despite the type of organ transplanted.

At this point, it is worth noticing that the variables chosen to assess the efficiency in the aforementioned studies were selected based on previous DEA studies and/or with the help of personnel somewhat involved in the transplantation system. In this way, to the best of our knowledge, this is the first manuscript to propose the use of a Causal Loop Diagram to visualize the whole process and support variable selection for the logistic transplantation process.

3 CASE STUDY

3.1 Organ Donation in Brazil

Transplantation and organ donation play a vital role in the lives of individuals who are in the terminal stages of illness or face a limited prognosis due to organ failure. Receiving a new organ, such as a kidney, heart, or lung, can enable these individuals to resume their work and social activities, ultimately leading to an improved quality of life (Garcia et al., 2015; WHO, 2020).

It is important to understand that organ transplantation involves the removal of organs from the donor and their subsequent implantation into the recipient who is awaiting transplantation. As such, the process of donation and transplantation is viewed as a connected and interdependent system, forming a cohesive and inseparable entity (Garcia et al., 2015; Gussen, 2014). This perspective is shared among scholars in the field and individuals involved in the entire process, recognizing the intricate relationship between organ donation and transplantation.

In the 1960s, Brazil initiated its activities in the field of organ transplantation for therapeutic purposes. However, it was not until 1968, with the implementation of Law No. 5,479, that the process of organ and tissue transplantation began to be formalized and organized throughout the country. Subsequently, in 1992, Law No. 8,489 was enacted, further enhancing the regulations that had been previously established (ABTO 2009; Moura & Silva, 2014).

The World Health Organization (WHO) recognizes two distinct systems with regard to the donation of organs and tissues. The first system is based on express consent, where individuals or their family members explicitly authorize the removal of organs for transplantation. In this system, individuals must actively opt in or sign a contract to indicate their willingness to donate. The second system is based on presumed consent, also known as exclusion, opting out, or contracting out. Under this system, the organs of the deceased can be extracted for transplantation purposes unless the individual explicitly expressed opposition to organ donation during their lifetime or if no family member objects to the donation (ABTO 2009; Moura & Silva, 2014).

In 1997, the establishment of Law No. 9,434, regulated by Decree No. 2,268, led to the creation of the National Transplant System (SNT) in Brazil. This legislation played a significant role in the organization and structuring of transplant activities in the country. It also brought about a fundamental change in the donation system, transitioning from presumed consent to express consent.

However, due to a lack of support and public adherence, in 2001, Law No. 10,211 reinstated the consented donation regime in Brazil. Under the current system, the donation of organs from deceased individuals requires documented authorization from the spouse or first or second-degree relatives, following the direct or collateral line. This legislation has governed the donation process in Brazil since then (ABTO, 2009; Brasil, 1997a, 1997b, 2017).

The management of all aspects related to organ and tissue transplantation in Brazil is entrusted to the National Transplant System (SNT), as stated by Brasil (2017). This includes overseeing the entire process, from the retrieval of organs and tissues to the completion of the transplantation surgery. The SNT plays a crucial role in ensuring the efficient and effective management of transplantation activities in the country.

Based on data from the Brazilian Transplant Registry (RBT) of the Brazilian Association of Organ Transplantation (ABTO), it was identified that Brazil has experienced an increase in effective organ donations. The rate of donations per million people (pmp) rose from 13.2 in 2013 to 18.1 in 2019, marking a 37% increase (ABTO, 2020).

However, as discussed in the introductory section of this work, the COVID-19 pandemic had a significant impact on transplantation activities. According to the 2021 Brazilian Transplant Registry (ABTO, 2022), the increase in donations was reversed due to limitations in available resources and the contraindication of transplants due to the high potential for exposure to the virus (ABTO, 2022).

Furthermore, according to the aforementioned ABTO report, the number of patients on the waiting list in 2019 was 37,946, while the number of effective donors was 3,768. On average, each individual donor provided just over six organs, resulting in a total of 24,157 organs donated. This means that the supply of organs met less than 65% of the demand (ABTO, 2020). Similar proportions were observed in previous years. It is important to note that not all organs collected in a given year were transplanted, with a process loss rate of 15%.

These statistics highlight that even without the impact of the SARS-CoV-2 pandemic, Brazil was already facing significant challenges in meeting the demand for organ transplantation. The pandemic has further exacerbated the situation, but it is evident that there were preexisting issues in the system, including the insufficient procurement and distribution of organs, as well as the wastage of scarce resources.

It is crucial to address these negative factors and work towards improving the efficiency and effectiveness of the organ transplantation system in Brazil, ensuring that more patients on the waiting list can receive life-saving transplants.

During the pandemic period, lung transplants were significantly impacted due to the risk of contamination for recipients. In 2021, only 83 lung donations were made in Brazil, while 1,681 were needed during the same period, resulting in a transplant rate of 0.4 per million people (pmp) (Brasil, 2021). However, it is worth noting that there was no significant variation or drastic reduction in comparison to previous years. From 2014 to 2019, before the pandemic, the average lung donation rate was 0.47 pmp (Brasil 2021).

Logistical problems play a significant role in the challenges faced in organ transplantation. According to the 1st Meeting of Basic Guidelines for Procurement and Removal of Multiple Organs and Tissues of the Brazilian Organization of Organ Transplants (ABTO), issues such as insufficient hospital beds, lack of equipment to identify brain death, and communication failures contribute to 5% to 10% of missed donation opportunities (ANDRIOLI 2015). Understanding and addressing these logistical aspects will be the focus of this research, aiming to propose improvements in the organ transplantation system.

3.2 Brazilian Organ Transplant System

The Brazilian National Transplant System (SNT – *Sistema Nacional de Transplantes*) bears the responsibility for orchestrating the intricate process encompassing the donation, retrieval, distribution, and transplantation of organs, tissues, cells, and segments of the human physique, all purposed for therapeutic endeavors (Brasil, 2017). The Technical Regulation of the SNT, ratified through Directive No. 2,600, endeavors to institute a contemporary and uniform modus operandi for this system, along with the formulation of precise norms and mechanisms, meticulously tailored to facilitate the coordination and governance of its constituent elements. The organizational framework of the SNT comprises a consortium of distinct entities (Brasil, 2009; Moura & Silva, 2014):

A) The General Coordination of the Brazilian National Transplant System (CGSNT – *Coordenação-geral do Sistema Nacional de Transplantes*) assumes the pivotal role as the central organ within the SNT framework. It operates as a coordination unit under the aegis of the Ministry of Health, specifically under the purview of the Department of Specialized Care (DAE – *Departamento de Atenção Especializada*) within the Secretariat of Health Care (SAS – *Secretaria de Atenção à Saúde*). The CGSNT is supported by the Strategic Advisory Group (GAE – *Grupo de Assessoramento Estratégico*) and the National Technical Chambers (CTNs – *Câmaras Técnicas Nacionais*) in the execution of its functions.

B) The Strategic Advisory Group (GAE) serves the purpose of providing support to the CGSNT, primarily tasked with formulating directives, suggesting enhancements to regulatory measures, identifying quality indicators, scrutinizing the data concerning SNT activities, and furnishing expert opinions when called upon to do so.

C) The National Technical Chambers (CTN) provide specialized technical assistance to the CGSNT in matters pertaining specifically to the processes of organ, tissue, and cell donation and transplantation.

D) The National Transplant Center (CNT – *Central Nacional de Transplantes*) serves as the entity responsible for overseeing the logistical coordination and distribution of organs and tissues in the national donation and transplantation process. Its primary duty lies in supporting the management of organ and tissue procurement and allocation, with the overarching aim of ensuring optimal utilization of available organs and equitable distribution.

E) The State Coordination's: These are overseen by the Health Departments of the States and the Federal District, or equivalent organizations. Their responsibilities encompass crafting supplementary regulations that harmonize with existing ones, establishing, accrediting, and supervising the Central Organ Notification, Procurement, and Distribution Center (CNCDO – *Central de Notificação, Captação e Distribuição de Órgãos*), authorizing the creation of Organ and Tissue Procurement Organizations (OPOs – *Organização de Procura de Órgãos e Tecidos*), and providing the CGSNT with updated information regarding transplant-related activities at the state level.

F) Central Organ Notification, Procurement, and Distribution Center (CNCDO): Its functions encompass the coordination of transplant activities at the state or district level, the management of the registry of potential donors, and the promotion and logistical organization of the distribution of organs and tissues within its operational jurisdiction.

G) Organ and Tissue Procurement Organizations (OPO): OPOs can be established by the Health Departments of the States and the Federal District, in collaboration with their respective CNCDOs, to which they must report. Their responsibilities encompass coordinating the logistics of donor procurement within their jurisdiction and integrating with the Intra-Hospital Committees for Organ and Tissue Donation for Transplantation (CIHDOTT – *Comissões Intra-Hospitalares de Doação de Órgãos e Tecidos para Transplantes*). Their primary objective is to facilitate the identification of donors, enable the diagnosis of brain death, and promote education on family support, brain death, and the donation/transplantation process in a comprehensive manner.

H) Intra-Hospital Committees for Organ and Tissue Donation for Transplantation (CIHDOTT): These are hospital committees, in some cases mandatory, with the purpose of orchestrating, within the healthcare facility, the organ donation protocol and facilitating the diagnosis of brain death (in accordance with the Resolution of the Federal Council of Medicine – CFM – *Conselho Federal de Medicina*). They are required to collaborate with their respective CNCDOs, OPOs, and/or tissue banks within their jurisdiction. Their objective is to streamline the process of organ and tissue donation and procurement, aiding in the identification and preservation of potential donors.

3.3 Brazilian logistical organization of the transplant

In the logistical aspect of organ transplantation, several factors come into play. The process involves packaging, storage, and transport of organs, taking into account their specific cold ischemia times and the distances between the donor and recipient locations. Scheduling operating rooms, ensuring the availability of necessary materials and equipment, and allocating specialized teams are also crucial considerations in the logistical scope (Gussen, 2014; Ratz, 2006). It is important to note that effective logistical planning relies on the successful allocation of the organ to its intended recipient. The logistical flow must be precise, fast, and flexible to ensure the timely delivery of the preserved organ from the donor to the recipient (Gussen, 2014; Ratz, 2006).

The organ transplantation process can be divided into two main phases: the harvesting phase and the surgery phase. The harvesting phase involves the search for the most suitable recipient and the logistical organization of the transplant, while the post-surgical phase mainly focuses on medical aspects such as surgical procedures, anti-rejection treatments, and post-therapies (Fuzzati, 2005).

Within the harvesting phase, there are three sub-phases: matchmaking, allocation of medical teams, and planning of transport routes. The matchmaking sub-phase involves analyzing the profiles of potential recipients on the waiting list and matching them with the available donor organs based on specific criteria (Fuzzati, 2005).

Overall, the logistical aspects of organ transplantation are crucial for ensuring efficient and successful procedures, and proper coordination and planning are essential to optimize the use of donated organs and improve patient outcomes.

In Brazil, the organ allocation system operates through a single list that includes regional, state, macro-regional, and national lists of potential recipients. These lists comprise individuals who are registered to receive specific types of organs, tissues, cells, or body parts, including Brazilian citizens, naturalized citizens, and foreigners residing in the country. The allocation of organs is organized at the macro-regional level, as depicted in Figure 2. The criteria for matching donors and recipients are based on various factors such as anthropometric, immunological, clinical, and serological characteristics of the donor and potential recipient (Brasil, 2009, 2017).

Region	Brazilian States and Federal District
Region I	Rio Grande do Sul (RS), Santa Catarian (SC) and Paraná (PR).
Region II	Rio de Janeiro (RJ), Minas Gerais (MG) and Espírito Santo (ES).
Region III	Gioás (GO), Mato Grosso (MT), Mato Grosso do Sul (MS), Distrito Federal (DF), Tocantins (TO), Amazonas (AM), Pará (PA), Acre (AC), Roraima (RR), Rondônia (RO), Amapá (AP) and São Paulo (SP).
Region IV	Bahia (BA), Sergipe (SE), Alagoas (AL), Pernambuco (PE), Paraíba (PB), Rio Grande do Norte (RN), Ceará (CE), Maranhão (MA) and Piauí (PI).

Figure 2 – Allocation of organs macro-regional organization.

Source: adapted from Brasil (2017) and Brasil (2009).

After the recipient is determined, the logistical process involves planning the transport route and allocating and scheduling the medical teams involved. The transport route planning includes determining the route and mode of transportation for the organ from the donor's hospital to the recipient's hospital. The choice of transport mode is crucial for the success of the transplant, as it directly affects the cold ischemia time of the organ, which is the time during which the organ is deprived of blood flow and oxygen (Carrara, 2014).

The scheduling of medical teams encompasses reserving operating rooms and organizing teams for both organ retrieval and transplant surgeries in recipients (Fuzzati, 2005; Gussen, 2014). This ensures that the necessary facilities, equipment, and personnel are available at the designated time to carry out the procedures efficiently.

Regarding the transportation of organs, Resolution-RDC No. 66 of 2009, issued by the National Health Surveillance Agency (ANVISA) in Brazil, regulates the transport of human organs in hypothermic conditions for transplant purposes within the country. According to this resolution, transportation includes various activities such as conditioning, packaging, labeling, signaling, transfer, temporary storage, transshipment, delivery, and receipt of the transported organ. The transportation process must be organized and coordinated between the sender, transporter, and recipient, following appropriate timeframes for each type of organ and adhering to biosafety norms to ensure the quality, safety, and integrity of the organ (ANVISA, 2009).

These guidelines and regulations aim to ensure the efficient and secure transportation of organs, minimizing the risk of damage or compromise to the organ's viability, and ultimately contributing to the success of the transplantation process.

Indeed, ensuring efficient and timely transportation of organs is crucial for the success of organ transplantation, and logistical deficiencies can hinder the process. Packaging, storage, and transport of organs, as well as considering the ischemia time and distances involved, are critical aspects of the transplantation process (Ratz, 2006).

To address these challenges and manage the technical, ethical, and legal aspects of the donation-transplantation process, Brazil has implemented the National Transplant System (SNT). The SNT adopts a single queue system to coordinate the allocation of organs, human resources, materials, and information, ensuring that all activities are carried out according to the established schedule (Leão, 2012).

The single queue system in Brazil encompasses regional, state, macro-regional, and national lists of potential recipients. It allows Brazilians, including those who are born, naturalized, or immigrants residing in Brazil, to register for organ transplantation (Brasil, 2009, 2017). The macro-regional organization defined by the National Transplantation Coordination (CNT) aims to prioritize coordination between nearby states and those with better interstate infrastructures, facilitating logistics related to recipients, organs, and medical teams that may require transportation (Brasil, 2009, 2017).

This organization and coordination within the single queue system help optimize the allocation of organs, improve logistical efficiency, and ensure equitable access to transplantation opportunities for patients throughout the country.

4 RESULTS AND DISCUSSION

4.1 Causal loop diagram of Brazilian Organ Donation Logistics

To identify the variables that would be used in the present study, searches were carried out in governmental and ABTO databases to find available data on the variables presented in the causal diagram, precisely to ensure that the chosen variables could be analyzed. After choosing the variables, the Causal Loop Diagram was created as a visual representation of the key variables of the system, their relationships, and the feedback loops between them. The idea was not to simulate the system in a complete application which should have included a stock-flow model, but only to begin an understanding of the system's behavior and its complexity, using it as a qualitative problem structuring methods, as proposed by Mingers & Rosenhead (2004).

The following steps were taken for the Causal Loop diagram development:

- Understand the flow, stages, activities and tasks related to organ transplantation and logistics in Brazil (section 2.2);
- Define model boundaries;
- Identify, through a critical analysis and research in scientific works, of which variables would be considered in the model;
- Use of the Vensim PLE software version 8.2.1 for the development of the relations of the selected variables and their feedback loops.

To begin constructing the Causal Loop Diagram (CLD), it is necessary to define its boundaries and main subsystems. Several key themes fall outside the scope of the CLD, such as the recruitment of potential donors, evaluation and medical criteria, maintenance and follow-up of donors and recipients, family interviews, allocation criteria, allocation processes, pediatric cases, organ acceptance criteria, regulations, surgical preparation, results, and documentation of all kind, as the one related to brain death, for example. These topics, while important, are beyond the scope of the CLD.

On the other hand, within the model, the variables that are included but may require further development to establish cause-and-effect relationships are effective donors, transplants, donation campaigns, and the waiting list.

Finally, the main subsystems of the model are transplant planning, transport, and organ/tissue quality. These subsystems are critical for ensuring the viability and successful transportation of organs for transplantation.

The overall structure and relationship between these subsystems and variables can be represented in a model, as shown in Figure 3. This model allows for a comprehensive understanding of the factors and processes involved in organ transplantation, with a focus on organ quality, transplant planning, and transport as key elements.

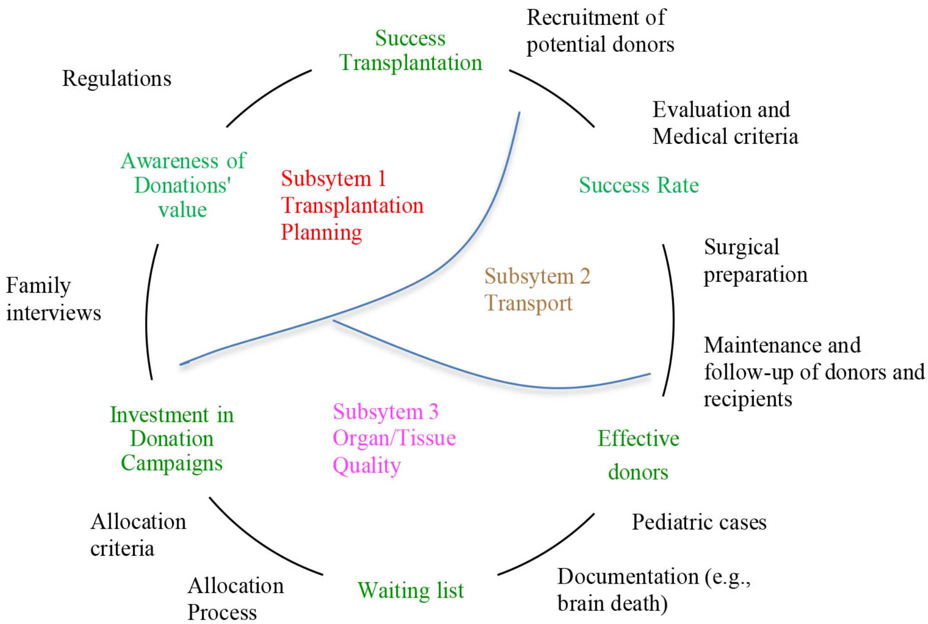


Figure 3 – Boundary of the model.

Regarding the variables included in the model, a critical analysis was conducted on the variables identified in Section 2.2 of the Literature Review. These variables served as a reference for the present study. From the four variables situated at the edge of the model, six variables were derivate (effective donors, successful transplantation, success rate, waiting list, investment in donation campaigns, awareness of the value of transplants), and Table 7 provides relevant references from the literature. It is worth noting that these variables have been addressed in various studies on the subject. In the current work, these variables will be utilized to establish relationships among the model's variables, without delving into the details of each topic. For instance, the waiting list will be included in the model to assess the impact of performed transplants, without specific considerations for new entries, exits, or other factors related to the list.

The model consists of three interconnected subsystems that delve into the variables related to the logistics of organ transplantation. The first subsystem, transplant planning (Table 8), primarily focuses on the state's CNCDO (State Center for Organ and Tissue Distribution) and examines the number of planned transplants based on the number of effective donors. This subsystem includes variables related to the capacity utilization of the center, such as the required capacity per donation, the number of staff members, the availability of transportation equipment, and the availability of medical teams. Additionally, it considers factors such as time to perform a recipient selection, the relationship between transport time and organ ischemia time, the number of compatible recipients, and the distance between the donor and recipient.

Table 7 – Variables in the Boundary.

VARIABLES INCLUDED	REFERENCES	ORIGINAL VARIABLES PROPOSED BY REFERENCES
Effective donors	Devi et al. (2010); Hirsch et al. (2012); Paricio & Figal (2015)	Donations; Organs for transplant; Total available kidneys
Sucessful Transplantation	Devi et al. (2010); Hirsch et al. (2012); Paricio & Figal (2015); Cruz et al. (2019)	Successful transplants; Transplanted patients
Success rate	Hirsch et al. (2012)	Acceptance rate
Waiting List	Devi et al. (2010); Hirsch et al. (2012); Paricio & Figal (2015); Cruz et al. (2019)	Waiting List; Active waitlist; Waiting list for a kidney transplant; Transplant Waiting List
Investment in donation campaigns	Devi et al. (2010); Hirsch et al. (2012)	Awareness due to close friends/family transplants; Awareness due to media campaign
Awareness of the value of transplants	Paricio & Figal (2015)	Campaign Efectiveness; Awareness campaigns;

The variables listed in the literature were adapted to suit the specific context of the model. For instance, variables like "number of collaborators" and "number of medical teams available" were derived from the variable "OPO staff" (personnel from the Organ Procurement Organization) but were tailored for the CNCDO in this model, accounting for the division of specialized agents and medical professionals. Other variables were introduced based on research materials. For example, ischemia time, which is a crucial factor in the logistical stages of organ transplantation, was not found in the consulted models that focused on other aspects. However, it is an essential variable to analyze from a logistics perspective.

The transport subsystem (Table 9) focuses on three variables, all of which have similar references in the literature. The first variable addresses the importance of coordinating different modes of transport effectively. "Efficient management of transportation modes" aims to reduce transport times and ensure optimal organ preservation, as suggested by Orjuela-Castro et al. (2016) in their study on the physalis fruit supply chain in Peru. Additionally, the variables of "transport speed" and "total transport time" are also considered in this subsystem.

Lastly, the Organ/Tissue Quality subsystem (Table 10) includes three variables, all of which have similar references in the literature. The variable "conservation level" is discussed in various studies and, in the context of organ transplantation, it primarily depends on the preparation and preservation of the packaging. The variables "organ quality" and "packaging compliance with regulations" are also important considerations within this subsystem.

Table 8 – Variables of the Transplant Planning Subsystem.

VARIABLES INCLUDED	REFERENCES	ORIGINAL VARIABLES PROPOSED BY REFERENCES
Required capacity per donation	Hirsch et al. (2012)	Capacity needed per transplant and Staff per needed organ
Number of staff members	Hirsch et al. (2012)	OPO Staff
Availability of transportation equipment	–	
Availability of medical teams	Hirsch et al. 2012	OPO Staff
Capacity utilization of the state center	–	
Number of planned transplants	–	
Time to recipient selection	-	
Number of compatible recipients	Devi et al. (2010)	
Paricio & Figal (2015)	Crossmatching and success rate; Kidneys from allocations priority policy going to transplantation were converted to compatible recipients.	
Distance between the donor and recipient	Fu & Shuai (2015); Zhang & Liu (2018)	
Devi et al. (2010)	Transport distance; Transport distance influence factor; Sent to other hospitals	
Estimated transport time	Orjuela-Castro et al. (2016)	System total time
Organ ischemia time (limit)	ANVISA (2009)	–

Table 9 – Variables of the Transportation Subsystem.

VARIABLES INCLUDED	REFERENCES	ORIGINAL VARIABLES PROPOSED BY REFERENCES
Efficient management of transportation modes	Orjuela-Castro et al. (2016)	Use of intermodal system
	Orjuela-Castro et al. (2016)	Articulation of transportation modes
Transport speed	Orjuela-Castro et al. (2016)	Transportation system speed
Total Transport Time	Orjuela-Castro et al. (2016)	System total time

Table 10 – Variables of the Organ/Tissue Quality Subsystem.

VARIABLES INCLUDED	REFERENCES	ORIGINAL VARIABLES PROPOSED BY REFERENCES
Conservation Level	Devi et al. 2010; Fu & Shuai (2015); Zhang & Liu (2018); Orjuela-Castro et al. (2016); Orjuela-Castro & Andarme-Jaimes (2018)	Rate of outdation; Damage to cargo volume; Transport cargo damage quantity; Conservation mechanism; Food security; Freshness
Organ Quality	Orjuela-Castro et al. (2016); Hirsch et al. (2012)	Product quality; Organ quality
Packaging compliance with regulations	ANVISA (2009); Orjuela-Castro et al. (2016)	Compliance with the quality requirements

Thus, a total of 23 variables were mapped to the model (Table 11) and they are colored by the subsystem they represented in the Causal loop Diagram (Figure 4).

Table 11 – Total number of variables in the model.

	# Variables
Subsystem 1: Transplantation Planning (in red)	11
Subsytem 2: Transport (in brown)	3
Subsystem 3: Organ/Tissue Quality (in magenta)	3
Variables in the Boundary (in green)	6
Total	23

First, the transplant planning subsystem has a larger number of variables and consists of two main components/aspects. The first component focuses on the evaluation of the *occupancy of the state center* and its capacity to meet the demand, considering limitations such as the *number of staff members*, *medical teams*, and *transportation equipment*. At the same time, the conversion of an *effective donor* into a *planned transplant* depends on the logistical assessment of the case to determine if there is a *compatible recipient available within a suitable timeframe* for the transplant. This timeframe is determined by the *estimated transport time* (using the available mode of transportation) and should not exceed the *organ's ischemia time*, which is particularly critical for heart transplants with a limited window of 4 hours.

Regarding the *occupancy of the state center (CNCDO),* an increased required *capacity per donation* would lead to a decrease in occupancy. Similarly, an increased *number of staff members, transportation equipment, and medical teams* would also have a similar impact on *occupancy*, explaining the negative relationships with opposite directions. A higher *occupancy* would result in a lower *number of planned transplants* due to the burden on the CNCDO, leading to a decrease in occupancy. This relationship between these two variables creates a balancing feedback loop labeled as B1, indicating that the *number of planned transplants* is constrained by the *oc-*

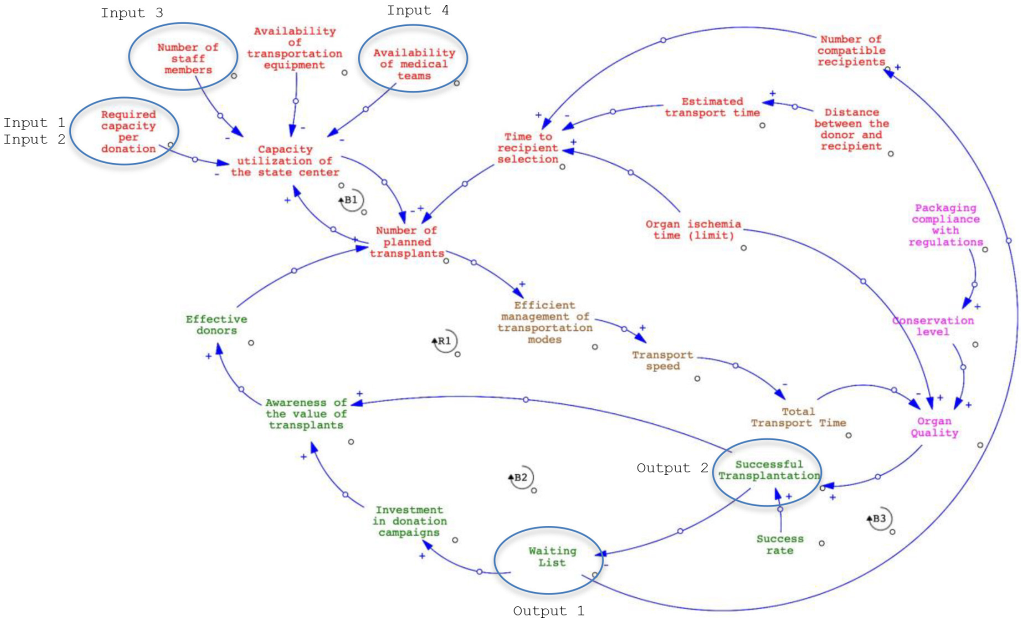


Figure 4 – Organ Donation Logistics – Causal Loop Diagram and DEA InputsOutputs.

cupancy, which represents the available capacity of the state center to meet the demands with its *staff members*, *medical teams*, and *transportation equipment*.

At the same time, a higher availability of timely recipients would result in a greater *number of planned transplants*. This availability depends primarily on three variables: the *number of compatible recipients, the estimated transport time, and the organ ischemia time*. In the case of the *number of compatible recipients*, the relationship is positive because a higher number of compatible recipients would lead to a greater *availability of timely recipients*. On the other hand, the *estimated transport time* depends on the *distance between the donor and the recipient*. Therefore, as the distance increases, the estimated transport time would also increase, resulting in a lower availability of timely recipients.

Lastly, the *organ ischemia time* plays a role in the availability of compatible recipients. A longer organ ischemia time would lead to a higher availability of timely recipients since there is a more extended time limit for transportation.

The transport subsystem illustrates that a *higher efficiency in coordinating modes of transport* would lead to increased *system speed* and, consequently, result in shorter *organ transport time* between the donor and the recipient.

In conclusion, the organ quality subsystem also plays a crucial role in the overall process. It depends on factors such as the *compliance of packaging with regulations*, which directly influences the *preservation level* and, consequently, the ultimate *quality of the organ*. However, beyond the variables within this subsystem, *organ quality* is also directly impacted by *transport time and* *ischemia time*. A shorter *transport time* contributes to higher *organ quality*, while exceeding the *ischemia time* renders the organ unsuitable for transplantation. It is therefore essential to comprehend the relationships between all variables and, particularly, the dynamics of the feedback loops.

Utilizing the Causal Loop Diagram (CLD) aids in providing a more comprehensive and structured understanding of the problem at hand, encompassing its multiple perspectives. This diagram facilitates the exploration of interconnections among variables, enabling a holistic analysis of the system's dynamics and feedback loops. By visually representing the cause-and-effect relationships, the CLD helps to unravel the complexity of the problem and supports a more nuanced and nuanced examination of the variables involved. This choice was based on its capacity to consider the influence of one variable on another during simulations, making it highly suitable for analyzing the logistics chain of organ transplants in Brazil, which is the focus of this study. According to Bowersox & Closs (2001), this diagram offers benefits in analyzing and comprehending logistical aspects.

The causal diagram (Figure 4) developed in this study offers a comprehensive analysis of the examined process and provides diverse perspectives on the same context. It complements the linear programming model proposed by Data Envelopment Analysis (DEA), as both methodologies consider the interdependencies among variables, aligning with the System Dynamics approach.

The primary objective of this qualitative System Dynamics (SD) model is to understand and analyze the relationships among variables and their feedback loops within the system. This understanding enables an examination of how each variable impacts the system's outcomes. By proposing and comprehending these relationships, it becomes possible to select variables for studying the efficiencies of each Brazilian state and the Federal District using Data Envelopment Analysis.

Following this approach, all variables with available data were categorized as potential inputs or outputs to determine the type of efficiency analysis that could be conducted. As a result, six variables were identified to study the efficiency of the Federative Units in conducting transplants with their available resources. The subsequent subsection will present the selected model and its variables.

4.2 Efficiency Assessment of the Brazilian Organ Transplantation Logistics

Once the analysis of the Causal Loop Diagram is performed, the efficiency assessment of the Organ Donation Logistics of the federative units (UFs) will be done using DEA. Therefore, each federative unit (UF) that have performed transplants will be a DMU. It is worth noticing that, since different types of transplants require different levels of resource utilization (organ availability, logistics, surgery duration, mortality, etc.), the efficiency analysis focused on a specific type of transplant. For this study, kidney transplant procedures were chosen as they have the highest demand and the highest mortality rate on the waiting list (ABTO, 2020). The UF of Amapá and Roraima did not perform any transplants during the period, and the states of Sergipe and

Tocantins do not have available resources to carry out the procedure, thus they did not perform kidney transplants (ABTO, 2020). The states of Mato Grosso and Amazonas also did not carry out kidney transplants, and therefore, they would not be included in the assessment. However, since these DMUs have hospitals capable of performing the procedure, they were included in the modeling, assuming that resources were allocated to these states, even if they were not used. In this way, there are 23 DMUs for the analysis.

Regarding the variables, the inputs and outputs were identified based on the Causal Diagram of Organ Transplant Logistics in Figure 4, where the inputs and outputs are marked in blue. The variables "Available CIHDOTTs" and "Hospitals for Transplants" represent the "Required Capacity per Donation," extracted from the Causal Diagram in Figure 4**.**, which refers to the infrastructure needed to perform the surgeries. On the other hand, the "State Transplant Center + Available OPOs" represents the "Number of Staff Members" as a reference since this variable indicated whether the professionals at the centers were overwhelmed or idle. The "Available Medical Teams" depict the variable "Number of available medical teams." The "Number of deaths on the waiting list" represents the "Waiting List," and the variable "Successful Transplants" in the Causal Diagram is translated in DEA as the variable "Transplants performed." Cost and transportation-related variables were disregarded due to imprecision and lack of available data. Table 12 presents a summary of the data corresponding to the selected variables for efficiency evaluation of the 23 UFs. It is important to point out that the variable "Mortality on the waiting list" is an undesirable output in DEA, meaning it is a result of the process (output) to be reduce.

Table 12 – Inputs and outputs for the efficiency assessment.

	Inputs				Undesirable Output	Output
	(Input 1) Hospitals for Transplants	(Input 2) Available CIHDOTTs	(Input 3) State Transplant Center + Available OPOs"	(Input 4) Number of available medical teams	(Output 1) Number of deaths on the waiting list	(Output 2) Successful Transplants"
Minimum	1	1	1	0	0	0
Maximum	37	106	11	31	690	2064
Average	6,87	23,26	3,48	6,17	56,57	273,17

Regarding the model and its orientation, the CCR model with output orientation, model (1) in the previous section, will be used. The output oriented CCR model, which considers constant returns to scale (CRS), is used due to the similarity in effort and resources involved in the procedures and also, because the aim of this study is to understand how much more Federative Unit could transplant with the resources they already have. Besides, as explained previously, the single queue system adopted by the SNT does not consider differences among the Federative Units when allocating organs (the outputs), which further enhances the CRS assumption. Furthermore, as mentioned previously, to deal with the undesirable output, the variable "Number of deaths on the waiting list" will be treated as an input.

With these definitions, the SIADv3.0 software (Angulo Meza et al., 2005) was used to obtain the results. Out of the 23 UFs, five states were efficient (100%): Bahia, Goiás, Paraná, Pernambuco, and Santa Catarina. As expected, the two states without transplants had an efficiency of 0%. Overall, the average efficiency was 61.84%.

Analyzing the data, it is worth noting the states in the Southeast region: Espírito Santo, Minas Gerais, Rio de Janeiro, and São Paulo. These four states accounted for 53% of all transplanted organs in 2019, had 48% of all registered teams for kidney transplants, and possessed 46% of all hospitals available to perform this type of procedure. However, despite a higher allocation of resources, these states were not efficient. This situation could be explained by the resource allocation policy, which often does not take into account the verification of achieved results. Moreover, the reduced efficiency could also be a result of an insufficient number of specialized teams registered in relation to the volume of available hospitals, delays in the organ procurement team in finding potential donors, or inefficiencies in the State Transplant Centers in contacting teams and potential recipients. It is important to highlight that the transportation activity provided by each state and the associated variables in the Causal Loop Diagram, for which information was not possible to obtain, constitute one of the most expensive activities in logistics.

Regarding efficient managerial and/or operational practices (benchmarks), one of the results provided by DEA models, it was possible to observe that Pernambuco stood out as a benchmark for many inefficient states. Since a benchmark provides information about operational and managerial guidelines that can be adopted to improve performance in kidney transportation, it is necessary to analyze the logistical procedures and support logistics (such as psychologists, counselors, etc.) in Pernambuco (not limited to it, as there are other benchmarks, although this state is more prominent) to establish guidelines that can be used in other states to make their practices efficient.

On the other hand, regarding targets and goals for each variable that must be reached for the inefficient state to become efficient, DEA models provide this information for each inefficient state. Table 13 provides information regarding the output, the total number of kidney transplants, for three out of the 18 inefficient states. These three states have the lowest, average and higher efficiency to depict how the efficiency index is inversely proportional to the target level of kidney transplants.

In this table, it can be observed the percentage increase proposed by the DEA model used for kidney transplants if resources had been used efficiently. The higher the efficiency, the lower the "effort" required to achieve efficient values in the output, i.e., the number of kidney transplants, and vice versa. Thus, for São Paulo, the necessary increment to become efficient is only 7% in transplants, while in the worst case, Paraíba needs a 256% increment. Considering the targets for all inefficient states, excluding those with zero transplants, we have an average increase of

Table 13 – Excerpt of target for inefficient DMUs.

UF	Number of kidney transplants		Standard Efficiency index	Increase %
	Actual	Target		
São Paulo	2064	2207	0,9352	7%
Piauí	18	24	0,7371	36%
Paraíba	38	135	0,2810	256%

194% in the total number of kidney transplants in Brazil, which represents a significant number indicating the potential increase in the number of transplants if resources are used efficiently.

Finally, it is possible to rank the states based on the normalized composite efficiency index, which allows distinguishing between efficient DMUs, as explained in Section 2. Additionally, the inverted frontier allows identifying the DMUs with the worst performances in some variables, which are often not identified since the standard efficiency index is benevolent in highlighting the best aspects (performances in variables) of a DMU. When calculating the composite efficiency, the DMU must have good performance in the variables in which it excels while not having poor performance in the variables that do not stand out.

Thus, Table 14 presents the results for the five efficient states considering the standard efficiency (Pernambuco, Santa Catarina, Paraná, Bahia, and Goiás), Espírito Santo, which has an average standard efficiency, and the state of Alagoas, which had an inverted efficiency index equal to 1, with a higher index indicating poorer DMU performance. Among the five efficient states, it can be highlighted that the composite efficiency index allowed distinguishing between the efficient states, with Pernambuco being ranked first, indicating that the state does not have weak performance in the variables considered in this analysis compared to other states. Regarding Espírito Santo, which has a composed efficiency of 38.99%, it is a state that has good characteristics (62.66% standard efficiency); however, it performs badly at some others (85.91%). On the other hand, Alagoas had an inverted efficiency index equal to 1, which signifies low performance in some variables. The weak performance in the standard efficiency already indicated weak performance in its "best" characteristics. Analyzing the data for the state, even with limited resources, it had a high level of mortality and low levels of kidney transplants compared to other states. Considering all 23 states in the analysis, the average efficiency was 61.84%, the inverted efficiency was 21.26%, and the normalized composite efficiency was 71.42%. In this way, the inverted frontier, along with the composed efficiency, allows to identify misused resources in the logistic chain that are not transforming into kidney transplant with reduce mortality.

In sum, as identified in the Causal Diagram, it is confirmed that the more resources available, the greater the number of transplants performed in a specific location, and the lower the burden on the State Centers, which in turn can better plan the transplants to be carried out. As a result, greater efficiency in the logistics chain occurs, leading to improved quality in both information flow and organism conditions, resulting in an increased number of successful transplants. It should be

Table 14 – Ranking using the normalized composed efficiency index of some DMUS.

DMU	Efficiency index			
	Standard	Inverted	Compost	Compost*
Pernambuco	100%	3.16%	98.42%	100%
Santa Catarina	100%	5.28%	97.36%	98.92%
Paraná	100%	5.96%	97.02%	98.58%
Bahia	100%	13.95%	93.02%	94.52%
Goiás	100%	22.67%	88.67%	90.09%
Espírito Santo	62.66%	85.91%	38.38%	38.99%
Alagoas	5.84%	100%	2.92%	2.96%

noted that there are limitations in data availability regarding transportation for each Federative Unit (Figure 2), and this is the reason why such variables are disregarded in the present study, although they are extremely relevant due to their impact on logistic costs.

5 CONCLUSIONS

This study addresses a relevant topic to Brazilian society, organ transplantation, with an application that provides a broader view of the process steps that can be improved through the use of a multimethodology that incorporates the Causal Loop Diagram into the Data Envelopment Analysis (DEA) approach for efficiency evaluation.

Furthermore, despite the historical increase in the number of transplants performed and the growing awareness in society, it is evident, as discussed in this article, that there is an inability to meet the needs of all individuals requiring a new organ. However, increasing the number of transplants performed depends not only on increasing the number of donors but also on developing an efficient and effective system. In 2019 alone, 2,484 people died while waiting for an organ, with 52% of these deaths being individuals in need of a kidney. By combining System Dynamics (SD) and DEA, it was possible to identify good management practices and opportunities for improvement among the analyzed Federative Units.

The integration of System Dynamics (SD) and Data Envelopment Analysis (DEA) facilitated the identification of effective management practices and areas for improvement among the examined Federative Units. This multimethodological approach offers a distinctive perspective, as it enables policy makers to assess resource utilization and promote equitable distribution through DEA, while simultaneously providing a systemic understanding of the decision-making process through qualitative System Dynamics results. By combining these two methodologies, a comprehensive and holistic view of the analyzed system is achieved, allowing for a more informed and strategic approach to decision making.

The aforementioned observations hold particularly true when considering the B2 feedback loop depicted in Figure 4. It becomes evident that an increased number of effective donors has a direct impact on the number of planned transplants by the state center. This, in turn, necessitates a higher level of efficiency in coordinating transportation modes to effectively meet the demand. As a result, transportation times are reduced, positively influencing the quality of organs being transported. The improved quality of grafts subsequently contributes to a greater success rate in transplant procedures, thereby decreasing the overall waiting list. As the demand for transplants decreases and fewer patients remain on the waiting list, the investment in donation campaigns diminishes. Consequently, the general awareness and recognition of the value of transplantation decreases, leading to a decline in the number of effective donors. This interconnected feedback loop establishes an equilibrium cycle whereby an increase in the number of donors ultimately leads to more transplants, fewer individuals awaiting transplantation, reduced investment in campaigns, and, consequently, a decline in the number of donors.

However, the R1 loop represents an alternative perspective centered around awareness and sensitization generated organically through successful transplants of close acquaintances or through media stories. The flow from a higher number of effective donors to an increased number of successful transplants follows the same logic as the B2 cycle. However, this increase would result in greater awareness of the value of transplants among friends, family members of recipients, and individuals who are moved by the stories and positive outcomes. Over time, this heightened awareness could potentially lead to an increase in the number of effective donors as more people enroll for organ donation.

The last feedback loop of the model (B3 loop) effectively portrays one of the characteristics of a complex system: counterintuitive behavior. Essentially, an increase in the number of successful transplant procedures would lead to a reduction in the waiting list, which, in turn, would also decrease the number of potential compatible recipients. Consequently, this would result in a decrease in the availability of recipients within a suitable timeframe, a decrease in the number of planned transplants, a decline in the efficiency of coordinating transportation modes, and a decrease in speed. These effects would subsequently lead to an increase in transport time, a reduction in organ quality, and ultimately a decrease in the number of successful transplant procedures. In other words, reducing the waiting list ends up diminishing the possibilities of finding compatible recipients for the available organs, which is a response that deviates from the system's intended objective.

Concerning the DEA approach, after analyzing the Causal Loop Diagram, it was possible to select six variables to assess the efficiency of the logistical aspect of the transplantation process. So, with these variables, the output-oriented CCR model and data from the year 2019, the efficiency of the FUs was determined. The CRS assumption used by the CCR model was considered in this manuscript, despite differences in “scale” and “size” among the FUs, which was done mainly because of the single queue system by the SNT independent from the place of origin or demand. As suggested by previous studies in Brazil (mentioned in Section 2.4), the results of the present study show a disparity in efficiency among the Federative Units. Furthermore, through the utilization of the inverted frontier and the composed efficiency, the efficiency measurement of each state incorporates both positive and negative attributes. This approach offers valuable insights into the specific variables that require attention for enhancing efficiency in the assessment process.

Moreover, it is important to point out that, to the best of our knowledge, this is the first manuscript to propose the use of System Dynamics to picture the whole organ transplantation process and support variable selection for the efficiency assessment the logistical aspect of the process using Data Envelopment Analysis.

As future research, it would be important to analyze the management practices of efficient DMUs beyond the numbers, but this analysis goes beyond the scope of the proposal presented here. Therefore, the continuity of research is identified as a topic for future work, evaluating the opportunity for further publications and knowledge exchange among State Transplant Centers regarding the actions each one uses to improve the National Transplant System as a whole.

Furthermore, the efficiency analysis of transplants can be conducted using the BCC model, which assumes variable returns to scale. This would allow to take into account the size and/or scale of the inputs but it would allow to set less demanding targets than the CCR model used in this study. Thus, the results of both models may be used by states to establish gradual improvement goals, first based on the results provided by the BCC model and subsequently incorporating those from the CCR model. Note that, the BCC model results must use with care as it identifies the DMU with the lowest (highest) input (output) as efficient (Dyson et al., 2001) and increases the number of efficient DMUs.

Finally, after the SARS-CoV-2 pandemic, some studies have focused in assessing the consequences in the organ transplant system, as is the case of Manoel et al. (2023). They used DEA and the Malmquist Index to assess the impact that the pandemic caused by the novel coronavirus in Brazil on specific aspects of the organ donation and transplantation process. In this way, provided the availability of data, future studies may analyze the impact of the pandemic in the transplantation process and the support of the appropriate Causal Loop Diagram.

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APPENDIX A

Table A1 – Inputs and outputs for the efficiency assessment, complete dataset for kidney transplants.

	Inputs				Undesirable Output	Output
Federative Unit	(Input 1) Hospitals for Transplants	(Input 2) Available CIHDOTTs	(Input 3) State Transplant Center + Available OPOs”	(Input 4) Number of available medical teams	(Output 1) Number of deaths on the waiting list	(Output 2) Successful Transplants”
Acre	1	4	2	1	0	4
Alagoas	2	6	2	3	11	7
Amazonas	1	6	2	0	0	0
Bahia	3	15	8	8	66	301
Ceará	7	20	5	5	22	293
Distrito Federal	7	12	2	5	5	86
Espírito Santo	4	37	1	2	135	100
Goiás	3	1	1	3	78	219
Maranhão	1	5	1	1	5	25
Mato Grosso	2	2	1	0	0	0
Mato Grosso do Sul	1	5	2	1	4	21
Minas Gerais	19	60	11	20	149	684
Pará	4	9	2	5	3	58
Paraíba	3	7	1	2	18	38
Paraná	18	60	4	15	4	587
Pernambuco	7	20	5	3	19	382
Piauí	2	1	2	2	3	18
Rio de Janeiro	13	80	5	15	25	497
Rio Grande do Norte	3	8	1	3	9	82
Rio Grande do Sul	14	41	8	9	37	491
Rondônia	1	2	2	1	5	17
Santa Catarina	5	28	1	7	13	309
São Paulo	37	106	11	31	690	2064