HFMEA-Fuzzy: evaluation of the main lean wastes in an Emergency Care Unit (ECU) in Rio de Janeiro

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Abstract
The aim of the article was to use HFMEA-Fuzzy modeling to evaluate the eight lean wastes and identify critical processes related to them. To achieve this, data was collected from an Emergency Care Unit (ECU) in Rio de Janeiro. The results showed that the Processing/Creativity waste was the most frequent, followed by Defects, Waiting/Inventory, and Overproduction waste. Additionally, it was possible to identify critical processes related to each waste and suggest improvements to reduce or eliminate these wastes.
Keywords: Healthcare Failure Mode and Effect Analysis; Logic Fuzzy; Lean Six Sigma.

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HFMEA-*Fuzzy*: avaliação dos principais desperdícios *lean* em Unidade de Pronto Atendimento (UPA) no Rio de Janeiro

Resumo

O artigo em questão teve como objetivo utilizar a modelagem HFMEA-*Fuzzy* para avaliar os oito desperdícios *lean* e identificar os processos críticos relacionados a eles. Para isso, foram coletados dados de uma Unidade de Pronto Atendimento (UPA) do Rio de Janeiro. Os resultados mostraram que o desperdício de Processamento/Criatividade foi o mais frequente, seguido do desperdício de Defeitos, Espera/Estoque e Superprodução. Além disso, foi possível identificar os processos críticos relacionados a cada desperdício e sugerir melhorias para reduzir ou eliminar esses desperdícios.

Palavras-chave: Análise de modo e efeito de falha na saúde; Lógica *Fuzzy*; *Lean* Seis *Sigma*.

HFMEA-*Fuzzy*: evaluación de los principales desperdicios *lean* en una Unidad de Pronta Atención (UPA) en Río de Janeiro

Resumen

El objetivo del artículo en cuestión fue utilizar la modelización HFMEA-*Fuzzy* para evaluar los ocho desperdicios *lean* e identificar los procesos críticos relacionados con ellos. Para ello, se recopilaron datos de una Unidad de Pronta Atención (UPA) de Río de Janeiro. Los resultados mostraron que el desperdicio de Procesamiento/Creatividad fue el más frecuente, seguido del desperdicio de Defectos, Espera/*Stock* y Sobreproducción. Además, se pudieron identificar los procesos críticos relacionados con cada desperdicio y sugerir mejoras para reducir o eliminar estos desperdicios.

Palabras clave: Análisis de modo y efecto de fallo en salud; Lógica *Fuzzy*; *Lean* Seis *Sigma*.

Introduction

The management of public health in Brazil is a topic of great importance and complexity, involving various aspects related to organization, financing, regulation and provision of health services to the population – National Health Survey (IBGE, 2019). Since the creation of the Unified Health System (UHS) in 1988, there have been significant advances in universalizing access to health services, with the creation of public policies aimed at promoting, preventing, diagnosing and treating diseases (GRAGNOLATI; LINDELOW; COUTTOLENC, 2013). However, there are still challenges to be faced, such as inequality in access to health services among different regions and social classes, inadequate funding and the need to improve the quality of services provided (TORTORELLA *et al.*, 2017).

In 1999, the Institute of Medicine (KOHN; CORRIGAN; DONALDSON, 2000) published the study "To Err Is Human: Building a Safer Health System", which pointed out the occurrence of between 44,000 and 98,000 deaths annually in the United States due to the low quality and reliability of processes related to healthcare. The study highlighted the need to improve the quality of healthcare processes and services to reduce failures and improve patient safety (HAVENS; BOROUGHS, 2000).

In this context, Emergency Care Units (ECUs) were created in Brazil in 2003, through the National Policy for Urgency and Emergency of the Ministry of Health (BRASIL, 2020). With the aim of offering fast patient care services and reducing queues in hospital emergency departments. The ECU's offer a simplified structure with X-ray, electrocardiography, pediatrics, laboratory exams and observation beds. However, like public hospitals, ECUs have also become part of the challenges of planning public policies, suffering from the same system failures as large institutions (O'DWYER *et al.*, 2013; COSENZA *et al.*, 2023).

Furthermore, the study noted that similar risk classification characteristics were identified in other health care facilities in Brazil where the Manchester Screening Method (MTS) was implemented. This consistency suggests that the issue of waste and efficiency in the use of resources may be a systemic challenge across the Brazilian health sector (PEREIRA *et al*., 2022).

Technical analysis also suggests a gap in knowledge about public health management and administration tools among UPA managers. This could imply that the lack of familiarity and understanding of these tools is contributing to the persistence of waste and inefficiencies. Thus, the study highlights the need for greater education and training in lean management and public health administration for the managers of these units, as a means of improving efficiency and reducing waste (SANTOS *et al*., 2021).

The main failures in the healthcare system are related to infrastructure, healthcare professionals' performance, lack of medication and medical supplies. However, the lack of organization in the workflow is one of the main difficulties faced by the public healthcare system in many countries (CARVALHO *et al.*, 2022). The workflow in a healthcare system is complex and involves several stages, from initial screening to treatment and follow-up (CHAVES *et al.*, 2023). If the workflow is not organized, it can lead to delays in care, medical errors and lower quality of care. Therefore, it becomes evident the importance of adopting systemic and structured methods for the identification, analysis and execution of plans to mitigate organizational failures (DREI; IGNÁCIO, 2022).

The reorganization of workflow is a common practice in many organizations, including the healthcare sector, to improve efficiency and the quality of services provided. A widely used approach for reorganizing workflow is the lean methodology, which aims to eliminate waste and increase efficiency (LEITE *et al.*, 2022). The lean methodology is based on a philosophy of continuous improvement, where all employees are encouraged to identify problems and propose solutions.

Lean Healthcare is an adaptation of lean methodology in the healthcare context. In Brazil, the application of Lean Healthcare in healthcare began to gain prominence in the early 2000s, with the implementation of pilot projects in hospitals and clinics. The São Camilo Hospitals Network and the Institute of Oncology of Vale do Paraíba were the pioneering hospitals in implementing Lean Healthcare in Brazil, starting the process of developing the methodology in 2007, according to Rodrigues and Affonso Neto (2017).

Lean Healthcare is essential that employees understand and share the proposed culture. When this occurs effectively, the changes and improvements proposed by the lean approach are more easily assimilated, maximizing the potential to positively influence the behavior of health professionals and, consequently, the results of patient care.

Some examples of studies that applied Lean Healthcare in public healthcare institutions in Brazil include: "Lean Principles applied in Healthcare Services: Five Brazilian Cases" (ARAÚJO *et al*., 2009); "Proposal for improving the management process of surgical waiting lists at the University Hospital of Brasília integrating the lean healthcare approach and system dynamics" (ALVES, 2018); "Implementation of Lean Healthcare: experiences and lessons learned in Brazilian hospitals" – Régis, Gohr and Santos (2018); "Lean healthcare approach to reduce costs in a sterilization plant based on surgical tray rationalization" (FOGLIATTO *et al*., 2020); "Systematic application of Lean Healthcare in a medium-sized medical clinic hospitalization" – Drei and Ignácio (2022) and others.

In this sense, Value Stream Mapping (VSM) emerges as a fundamental tool. In the context of terminal hospital cleaning, for instance, VSM creates a structured diagram that documents all the processes involved from the beginning to the end. By recording the duration of each step and identifying compliance and non-compliance with the Standard Operating Protocol - SOP guidance, not only can waste be pinpointed and quantified, but also bottlenecks and opportunities for improvement can be discovered (FREIRE; CALADO; PAES, 2021).

The purpose of this study is to demonstrate the application of a modeling developed by the authors called 'HFMEA-Fuzzy' for evaluating the eight wastes presented by Lean Healthcare. This modeling combines two methods: HFMEA (Healthcare Failure Mode and Effects Analysis), which is a systematic approach for risk analysis, and Fuzzy logic, which is an artificial intelligence technique that deals with uncertainties and imprecisions in decision making. It allows imprecise and subjective variables to be represented in mathematical terms, facilitating the analysis and understanding of these variables.

This modeling allowed us to evaluate the main types of wastes that did not add value to the activities or processes considered important in the Emergency Care Unit located in Rio de Janeiro. Therefore, this study aims to answer three research questions:

1. How to quantify and analyze the eight Lean Healthcare wastes in the Emergency Care Unit (ECU) through HFMEA-Fuzzy modeling?
2. What is the hierarchy of the main wastes in the studied Emergency Care Unit (ECU) through HFMEA-Fuzzy modeling?
3. What are the proposals for improvement for the analyzed wastes?

This article will exclusively address the identification of critical processes through the mapping of the eight wastes under HFMEA-Fuzzy modeling, presenting also some change implementations resulting from these findings. It is important to highlight that this modeling was created for simulation purposes. The data used in this study were employed to simulate the combination of two methods in a predictable and controlled environment. The simulation of this data enabled the evaluation of different scenarios and hypotheses without incurring in the risks and costs associated with real experiments.

Theoretical framework

Lean Healthcare - The Eight Wastes

Lean Healthcare is a management philosophy that aims to improve healthcare quality, reduce costs and increase efficiency (MANOS; SATTLER; ALUKAL, 2006). One of the main features of Lean Healthcare is the elimination of the eight types of waste, which were adapted to healthcare from Taiichi Ohno's (OHNO, 1997) original list, including:

- Waiting: unnecessary waiting time, whether for the patient or healthcare professionals.
- Overproduction: providing more care than necessary, wasting resources.
- Transportation: unnecessary movement of patients, professionals and equipment.
- Unnecessary processing: performing activities that do not add value, such as duplication of records or excessive data collection.
- Inventory: keeping medications, supplies, or equipment in excess, without immediate need.
- Motion: unnecessary movements of healthcare professionals that do not add value to the process.
- Defects: errors that lead to rework, corrections, or, worse, harm to the patient.
- Human Talent: not utilizing the full potential of the skills and knowledge of healthcare professionals.

By eliminating these eight wastes, Lean Healthcare can reduce patient wait times, improve process efficiency, increase patient safety, reduce costs and improve patient and healthcare professional satisfaction (WEINSTOCK, 2008). The elimination of waste is achieved through process analysis and identification of improvement opportunities, involving healthcare professionals in the search for solutions. Lean

Healthcare is a continuous improvement approach, where improvements are implemented gradually and systematically (MANOS; SATTLER; ALUKAL, 2006).

HFMEA

The HFMEA (Healthcare Failure Mode and Effects Analysis) methodology originated in the 1960s when NASA (National Aeronautics and Space Administration) developed the FMEA (Failure Mode and Effects Analysis) to assess and prevent failures in complex systems such as rockets and aircrafts (DEROSIER *et al.*, 2002; STALHANDSKE *et al.*, 2003). From then on, the FMEA methodology was adopted by other industrial sectors such as automotive and electronics to assess the reliability of products and processes. Later, the methodology was adapted to the healthcare field, resulting in the HFMEA (ADACHI; LODOLCE, 2005).

The HFMEA was initially developed in 1993 by a group of biomedical engineers from the VA National Center for Patient Safety with the goal of adapting FMEA to the healthcare field and improving patient safety (STAMATIS, 2015). Since then, the HFMEA methodology has been widely adopted in hospitals and healthcare systems worldwide as a systematic approach to identifying, evaluating and preventing failures in healthcare processes (STALHANDSKE *et al.*, 2003). The methodology is often used in conjunction with other continuous improvement tools and techniques such as Lean Healthcare and Six Sigma to improve healthcare quality and patient safety (COSENZA *et al.*, 2021).

According to Derosier *et al.* (2002), the HFMEA process consists of five steps to identify and prevent risks in patient care: 1. select the process that presents high risk or vulnerability; 2. formation of a multidisciplinary team and leader to perform the analysis; 3. representation of the analyzed process in a flowchart or diagram; 4. risk analysis: evaluation and scoring of each analyzed risk under the criteria of occurrence, detection and severity. It is worth noting that in step 4, the Risk Priority Number (RPN) is calculated, which is the value of the multiplication of the scores of occurrences, detection and severity of each failure mode analyzed.

The RPN is a useful metric to help prioritize risks and make decisions about corrective actions to be taken, as the higher the RPN, the higher the priority assigned to the risk, indicating that it needs more attention. 5. Define prevention actions: actions are determined to eliminate or reduce factors that cause risks to patient safety. Thus, the HFMEA tool allows not only mapping failures but also prioritizing and monitoring them through RPNs (SILVA *et al.*, 2022).

Logic Fuzzy

Fuzzy logic was conceived by the mathematician Lotfi Zadeh, a professor at the University of California, Berkeley, during the 1960s (ZADEH, 1978). Dissatisfied with the limitations of classical logic, which is based on binary values (true or false), Zadeh decided to explore a more flexible approach capable of dealing with situations where truth is not absolute, but rather a matter of degree. He then proposed a mathematical system that allowed for working with partial and imprecise values, where the terms "true" and "false" were not the only possible ones, but rather a *spectrum* of intermediate values between them (ZADEH, 1978). He referred to this approach as "fuzzy logic" or "fuzzy set theory" (ABBOD et al., 2001).

Zadeh (1978) goal was to create a system that could deal with human reasoning, which is often uncertain, imprecise and ambiguous, and cannot be expressed accurately in traditional mathematical terms (SHAW; SIMÕES, 1999). Therefore, the mathematician proposed a logical system that allowed the use of partial and imprecise values called "fuzzy values" (WEBER; KLAIN, 2003). According to Weber and Klain (2003), these values are expressed in terms of degrees of membership, which indicate how well an object or concept fits into a particular category. In other words, fuzzy logic deals with uncertainty and imprecision, allowing answers to be expressed in terms of probability rather than true or false.

While the boundaries of classical sets are well-defined (crisp logic), those of fuzzy sets are nebulous, that is, an attempt is made to approximate the imprecision of human reasoning. According to Zadeh (1978), in classical set theory, the concept of an element's membership in a set is well-defined. If there is fuzziness at the borders of the set, which cannot be limited within a crisp set, the membership function is defined as: $\mu A = X \rightarrow [0,1]$, where μA indicates how compatible x is with set A. The membership functions can be defined based on user experience and perspective, but it is common to use standard membership functions, such as triangular, trapezoidal, and Gaussian shapes.

It is considered that the membership functions μRij (rij) and μwj (wj) assume values in the interval [0,1]. All fuzzy sets are considered normalized, i.e., they have finite supports and assume the value 1 at least once. For the evaluation of an environment

Xj, a fuzzy set is assumed which is computed based on the values of rij and wj, where the vector z = (w1, w2, ...,wm, r1, r2, ..., rn). Equation 1 presents the membership function.

Equation 1: Pertinence function

$$f(z) = \frac{\sum_{j=1}^{m} w_j r_j}{\sum_{j=1}^{m} w_j}$$

The membership function for weighted degrees is given by:

$\mu_{\tilde{R}i}(\bar{r}_i)$ = sup ⌠zi(z) $\bar{r}_i$ □ R; Z: (z) = $\bar{r}$ i

The normalized value for alternative i is given by the expression:

Equation 2: Normalized Value

$$\bar{r}_i = \frac{\sum_{j=1}^{m} w_j r_{ij}}{\sum_{j=1}^{m} w_j}$$

If final degrees are crisp, r1, r2, ..., rn, then:

Equation 3: Fuzzy variable

$$p_i = \bar{r}_i - \frac{1}{n-1}\sum_{j=1}^{m} \bar{r}_j \, .$$

Given that the rij's and wj's are fuzzy variables, pi is also a fuzzy variable with a membership function □pi(p) = sup □R ($\bar{r}$1, $\bar{r}$2, ..., $\bar{r}$n) pi ∊ R; $\bar{r}$1, $\bar{r}$2, ..., $\bar{r}$n: □i ($\bar{r}$1, $\bar{r}$2, ..., $\bar{r}$n) = pi.

Finally, according to Zadeh (1978), linguistic variables are a way to represent uncertainty in a system. Instead of assigning precise values to variables, linguistic variables assign imprecise values that reflect uncertainty about the system. These values are expressed in linguistic terms, such as "high," "low," "medium," "very high," "very low," etc. Linguistic variables are used in fuzzy control systems, which use rules based on fuzzy logic to make decisions based on system inputs.

Methodology

Figure 1 presents the steps that make up the methodology proposed for this study.

Figure 1 - Methodology of this research

Source: The authors (2022).

The steps consisted of: 1. theoretical framework: mapping the research topics in the context of available literature, providing theoretical support for the research (arguments); 2. data treatment: this modality was carried out through documentary empirical analysis and synthesis of information taken from the reports received from the ECU, as well as describing the step-by-step considerations used for the elaboration of the HFMEA-FUZZY methods for the proposed modeling through the evaluation of the eight wastes and its application; 3. results and discussion: presentation and discussion of the findings.

Data Treatment

Data collection

This study aims to present the main wastes of an Emergency Care Unit (ECU) in Rio de Janeiro. This ECU was included in a project of the Federal Government of Brazil in partnership with the Federal Fluminense University in 2020. The project called "Lean in ECU" is an initiative that aims to apply Lean Healthcare philosophy in the health environment of ECU, with the objective of reducing waiting lines through the elimination of wastes. The Lean in ECU project was divided into several stages, including the identification of critical processes that needed improvement, the creation of a multidisciplinary team to lead the project in ECU, the analysis of the workflow, the implementation of changes and the monitoring of results.

Lean consultants are professionals specialized in applying Lean Healthcare concepts in organizations. For this reason, the Lean in ECU project established a team of lean consultants to be responsible for implementing improvement actions through weekly visits to the unit. These professionals worked with the objective of identifying and eliminating wastes in processes to increase the efficiency of the services offered.

In this context, the lean consultants, on their first visit, met the internal team of the ECU and the unit itself, and explained the scope of the project, as well as defined seven key people from the unit to participate in meetings for the implementation of Lean Healthcare at the ECU. Among them were receptionists, managers and nursing coordinators from the unit. It is worth noting that there were variations in the number of people in the ECU internal team, depending on the day of the consultants' visit to the unit. Thus, based on the initial explanations of the project scope, the consultants went to the work sectors of the unit (reception, examination rooms, offices, etc.) and listened to the ECU professionals (meeting participants) regarding the "pain points" and opportunities they perceived that could be addressed with the Lean Healthcare methodology. All information was documented.

As a result, a documentary analysis of the reports from each visit to the unit was prepared by the lean project consulting team to present what was executed on the current day according to the initial planning. Documentary analysis can be performed quantitatively, when seeking to extract numerical and statistical information from documents, or qualitatively, when seeking to understand the meanings and contexts present in the documents.

Therefore, this article will only address the identification of critical processes through the mapping of the eight wastes using HFMEA-Fuzzy modeling and will present some changes implemented based on the waste findings. It should be noted that this modeling was developed for simulation purposes. In general, the data used in this article served to simulate the combination of two methods in a controlled and predictable environment. Simulating this data allowed for the evaluation of different scenarios and hypotheses without the risks and costs associated with conducting real experiments.

Initial Diagnosis

The consulting team applied an initial diagnosis document to structure and understand the data and how the unit's processes work. The initial diagnosis is a table with three columns: the first column, "Wastes", relates the eight wastes to an evaluation objective of the unit, and the last column, "Key Points", is the questions used to identify whether the unit had such practices. The objectives were divided into 5 areas: 1) management/leadership for a lean environment; 2) adherence to communication and interaction among the team; 3) management through indicators; 4) physical and technological structure; and 5) clear and well-defined processes. It should be noted that each area has topics related to the theme addressed.

According to the consultants, the initial diagnosis is a practice dedicated to quantifying the performance of processes in organizations. Since at different points in the processes, the organization will generally be classified into certain levels based on characteristics that can be defined and aggregated to form a description of the organization's ability to understand and manage its processes.

Table 1 – Initial Diagnostic

WASTE	OBJECTIVE	IMPORTANT POINTS
Processing/Creativity (Unused talent)	Assessment of the Management/Leadership level for a lean environment	1. Respondents recognize the technical management skills of the leadership? 2. There is leadership involvement, follow-up and support on a daily basis? 3. Respondents perceive that roles and responsibilities are well defined? 4. Respondents are open to give their opinions and ideas? 5. Processes are clear and well defined? 6. It has a visual management framework? 7. In the management chart are the main indicators, routines of the period? 8. There is the use of *Kanban*?
Defects	Assessment of the level of adherence to communication and interaction among the team	1. There are alignment meetings with the team? 2. Meetings are held with predefined and disciplined frequency? 3. Meetings are perceived as effective? 4. There is a practice of Daily? 5. There is the practice of the Daily next to a management in sight? 6. The team respects each other and considers itself integrated? 7. Shift changes are structured and effective? 8. The team identifies problems quickly and resolves them quickly?

Continua

Conclusão

WASTE	OBJECTIVE	IMPORTANT POINTS
Waiting/Inventory	Evaluate the management level through indicators	1. There are Lead Time indicators (dwell time, queue time, among others)? 2. There are Process Cycle Efficiency (PCE) indicators? 3. There are productivity indicators per area? 4. There are indicators for quality? 5. There is a repository for the collected data? 6. The data leads to the construction of a report with a defined frequency for analysis? 7. Analyses are performed and actions are triggered? 8. Actions are validated and improvements are evidenced?
Overproduction	Assessment of the level of physical and technological structure	1. The unit uses the 5S methodology? 2. Equipment is working properly? 3. The spaces guarantee a good circulation especially during peak hours? 4. There are computers to process the data? 5. They use some kind of system to manage the ECU? 6. There is an adequate layout for patient care according to the Manchester protocol? 7. There are visual management practices? 8. The layout facilitates queue organization?
Transportation/Moving	Assessment of whether the processes are clear and well-defined	1. There is staff knowledge about the Fast Track process? 2. Fast Track is implemented in the ECU 24h? 3. If yes to question 2, what are the Fast Track indicators? 4. If no for question 2, have you tried to implement Fast Track at any time? 5. Can restrictions for Fast Track implementation be removed? 6. Is Fast Track applicable for ECU 24h? 7. Process Map is visible from ECU? 8. Staff knows the process flow of the ECU?

Source: ECU INTERNAL REPORTS (2022).

This diagnosis was presented at one of the consultant visits to the ECU, answered by the ECU professionals and scored according to the reality faced by the unit. The scores from this diagnosis were used for the purpose of this simulation, in order to transform them into "fuzzified" data under the evaluation criteria of HFMEA.

HFMEA Criteria

The score obtained from the initial diagnosis, corresponds to the amount of occurrence of good practices of the unit, in relation to its performance, to the checklist of 40 questions presented in Table 1. For example, to evaluate the management/leadership level for a lean environment, eight situations were presented in which the answers were "yes" or "no", so the computed value resulted from the amount of "no". In view of this, the criteria adopted for the preparation of the HFMEA waste analysis were defined through those in Table 2, in order to facilitate the calculations.

The HFMEA tool allows adaptations in its method for risk analysis. Several studies report such adaptation in the tables for obtaining the values corresponding to the parameters of occurrence, severity and detection as Tilburg *et al.* (2006) and Abrahamsen, Abrahamsen and Høyland (2016) who used the scoring matrix for severity (minor, moderate, major, catastrophic) as for probability (remote, uncommon, occasional, frequent) based on the definitions published by Derosier *et al.* (2002). In addition, Lanzetta et al., 2013 assigned risk values (1-10) to the 3 probability parameters, although the 1-5 scale would facilitate compliance among the team involved in the analysis (WELBORN; DHALIWAL, 2007).

Table 2 - HFMEA Criteria

POINT	OCCURRENCE	SEVERITY	DETECTION
02	1 point not met	Failure with little noticeable effect to patients and/or professional discriminated;	Almost certainly
04	Between 1 and 3 unmet points	Slight deterioration in performance with mild patient and/or professional dissatisfaction;	High
06	Between 4 and 5 unmet points	Significant deterioration in performance of a system with patient and/or professional dissatisfaction.	Moderate
08	Between 6 and 7 unanswered points	System ceases to function and there is great patient and/or professional dissatisfaction.	Remote
10	All points are not covered	Same as above but affects patient and/or professional safety.	Almost impossible

Source: The authors (2022) adapted from STAMATIS (2015).

Table 2 has the purpose of establishing the Occurrence (O), Severity (S) and Detection (D) rates of the failure by answering the questions:

(O) If the fault occurs, what is the chance that this type of fault will occur? Thus, the greater the number of points that are not met, the greater the chance that waste will occur;

(S) If the failure occurs, what damage can be generated? And, with this, score the failure according to the criteria selected through the index;

(D) If the failure occurs, what is the chance that it will be detected? And, with this, score the failure according to criteria selected through the index.

HFMEA Score

Table 3 presents the result under HFMEA criteria using the fuzzy scoring characteristics for analyzing the five metrics for evaluating the APU, as well as the related waste.

Table 3 - HFMEA Score Results

WASTES	ITEMS	OCCURRENCE	SEVERITY	DETECTION
Processing/ Creativity	Management/Leadership for a Lean Environment	6	6	2
Defects	Adherence to communication and team interaction	6	8	2
Waiting/inventory	Management through indicators	4	6	4
Overproduction	Physical and technological structure	4	8	2
Transportation/ Moving	Clear and well-defined processes	4	6	4

Source: The authors (2022).

Processing waste, creativity and defects had the highest occurrence rates. The score of number 6 shows that there are still points (activities) that were not practiced by ECU. Therefore, between 4 and 5 points were not met. Thus, the waste of processing/creativity shows inefficiency in management, as well as poor use of human talent. The sum of these failures leads the ECU to trigger the waste of defects, since this is associated with communication and interaction among the team. It is worth mentioning that as for the severity parameter the processing/creativity waste has significant deterioration in the system performance with dissatisfaction of the patient and/or professional, that is, both the patient and the ECU professional could be restless or even upset in the act of care.

The context of the ECU in the year 2020 was of pandemic and insufficient manpower for the demand at that time. For this reason, health professionals, in general, were working under pressure at work and on personal issues. The degree of severity of the waste defects shows that the lack of effective communication between the shift teams, between the leadership and all the professionals involved in the patient flow causes a non-functioning system with great dissatisfaction of the patient and/or professional. We also have that in terms of Detection both wastes could be seen as "Almost certainly".

A technique called RPN was used to prioritize the critical wasteful processes, with the following results:

Defects: 6x8x2= 96

Waiting/Inventory: 4x6x4= 96

Transport/Movement: 4x6x4= 96

Processing/Creativity: 6x6x2= 72

Overproduction: 4x8x2= 64

According to this technique, the wasteful processes Defects, Waiting/Inventory, and Transport/Movement are the ones that need to be prioritized for resolution of the worst causes. However, it is important to consider the severity of the impact, the frequency with which the cause occurs, and the ease or speed with which it can be resolved, to ensure that resources are directed to the areas where they will have the greatest impact.

Fuzzy Criteria

After defining the HFMEA criteria, the next step is to establish the criteria for adopting fuzzy logic, on a scale of [0.2 to 1]. The first stage consists of characterizing the degree of importance's and their respective weights in linguistic terms:

1: Very Important (VI) - Absence of the factor makes the process unfeasible;

0.8: Important (I) - Absence of the factor compromises the success of the process but does not make it unfeasible;

0.6: Relatively Important (RI) - Absence of the factor does not compromise the success of the process but makes it less attractive;

0.4: Slightly Important (SI) - Absence of the factor compromises/influences the success of the process;

0.2: No Importance (NI) - Absence of the factor makes the process unviable.

Demand Matrix

The second stage was to invite five professionals trained and experienced in the Lean Healthcare philosophy to evaluate and score the eight wastes as to their level of importance. Thus, contributing to the survey of the scores used for fuzzy logic. The Demand Matrix was elaborated, Table 4, based on the result of the professionals in lean by assigning the degrees of pertinence considering each of the five factors in order of importance.

Table 4 - Factors and pertinence degrees of the Demand Matrix

DEMAND MATRIX	PERTINENCE DEGREES				
Factors	**VI**	**I**	**RI**	**SI**	**NI**
1. Management and Leadership for a Lean Environment	0,67	1	0	0	0
2. Adherence to communication and team interaction	1	1	0,50	0	0
3. Management through indicators	0,67	1	0	0	0
4. Physical and technological structure	1	1	0	0,50	0
5. Clear and well-defined processes	1	0,67	0	0	0
Total	4,34	4,67	0,50	0,50	0

Source: The authors (2022).

Table 4, which represents the Demand Matrix, revealed that, according to experts, among the five factors analyzed, the two main ones are "Adherence to communication and interaction between the team". This result can be seen by adding the rows of each factor, so factors 2 and 4 obtained a value of 2.5. It is also possible to highlight that the degree of relevance "Important (I)" is the one that best suits the factors, in general, according to professionals, with a total of 4.67.

Supply Matrix

The Supply Matrix was elaborated based on Table 4, following the linguistic terms of the HFMEA tool:

Very High - High - Medium - Low - Very Low

Considering the following questions:

- Occurrence - What is the chance of this type of failure occurring?
- Severity - If the failure occurs, how much damage can be generated?
- Detection - If the failure occurs, what is the chance that it will be detected?

Matrix Crossing

Table 5 presents the Demand and Supply Matrix Crossing following the fuzzy logic hierarchization model.

Table 5 - Matrix Crossing

Demand x Supply					
	Supply				
Demand	Very High	High	Medium	Low	Very Low
Very Important	1	1-1/n	1-2/n	1-3/n	1-4/n
Important	1+1/n	1	1-1/n	1-2/n	1-3/n
Relatively Important	1+2/n	1+1/n	1	1-1/n	1-2/n
Slightly Important	1+3/n	1+2/n	1+1/n	1	1-1/n
No Importance	1+4/n	1+3/n	1+2/n	1+1/n	1
n = 5					

Demand x Supply					
	Supply				
Demand	Very High	High	Medium	Low	Very Low
Very Important	1	0,80	0,60	0,40	0,20
Important	1,20	1	0,80	0,60	0,40
Relatively Important	1,40	1,20	1	0,80	0,60
Slightly Important	1,60	1,40	1,20	1	0,80
No Importance	1,80	1,60	1,40	1,20	1
n = 5					

Source: The authors (2022)

One has a waste analyzed as having a "Very Important" demand and a "High" supply, the value in the crossing matrix presents the value of 0.8 or 80%. It means that 80% of these failures are causing this waste to occur, having a certain degree of severity involved, as well as a level of detection by those involved in the process.

Result and discussion

In this section, the results and discussion of the HFMEA-Fuzzy simulation regarding the eight Lean Healthcare wastes addressed throughout this article will be presented. It should be noted that this study aimed to answer three research questions:

1. **How to quantify and analyze the eight Lean Healthcare wastes in the Emergency Care Unit through HFMEA-Fuzzy modeling?**

Answer: the step-by-step process for this question is presented in the previous section "Data Treatment". Data treatment was an important process to ensure the accuracy, consistency and usefulness of the data. It served to transform raw qualitative information into meaningful quantitative information. Fuzzy transformation of the data allowed removing the ambiguities of the HFMEA method through the measurement scale, which involved assigning numerical values to different attributes and characteristics of the qualitative data, in this case, the wastes.

2. **What is the hierarchy of the main wastes in the ECU under study through HFMEA-Fuzzy modeling?**

Answer: the main result of this study is compiled in Table 6, which presents the cross-referencing of the Demand and Supply matrices, which means the hierarchy of wastes. The legend of Table 5 establishes that the value 1 - fully meets the expectation; close to 1 - slightly meets the expectation and above 1 - exceeds the expectation.

Table 6 - Waste Hierarchy Results

	RESULT OF THE DEMAND X SUPPLY MATRICES				
		ECU – RJ			
WASTES	**Factors**	**Occurrence**	**Severity**	**Detection**	**RPN**
Processing/creativity	Management and leadership for a Lean environment	0,8	0,8	1,2	0,77
Defects	Adherence to communication and team interaction	0,6	0,8	1,2	0,58
Waiting/inventory	Management through indicators	0,4	0,8	1,0	0,32
Overproduction	Physical and technological structure	0,4	0,8	1,0	0,32
Transportation/moving	Clear and well-defined processes	0,4	0,6	0,8	0,19
	Total - Fuzzy index	2,6	3,8	5,2	2,18
	Average - Fuzzy index	0,52	0,76	1,04	0,43

Source: The authors (2022).

The data from Table 3 (HFMEA Score Result) were "fuzzified", allowing the responses to be expressed in terms of degrees of membership, between 0 and 1. The HFMEA-Fuzzy modeling of the fuzzy logic hierarchy requires the "fuzzification" of these values since each of the HFMEA scores belongs to different levels of criticality of the fuzzy sets. The TOTAL - FUZZY INDEX presents the sum of each criterion and reveals that 52% of the waste is detectable and under the view of the users (professionals and patients) of the services provided in the ECU.

The AVERAGE - FUZZY INDEX reveals that considering the practices adopted in the ECU, in relation to all the waste and without the necessary improvements implemented, on average 52% of the waste is frequent, 76% of these generate significant damage to the system, for example, one waste triggers others. Lastly, the perception of failures is over 100% detectable.

In summary, the hierarchy of the wastes is determined by the values of the RPN, thus, it is possible to see in 1st place the Processing/Creativity waste, in 2nd place Defects, in 3rd place Waiting/Inventory and Overproduction, and finally, in 4th place Transportation/Movement. It is worth noting that the HFMEA criteria regarding the occurrence, severity, and detection indices were multiplied to find the RPN, and these parameters allowed for presenting the probability of failures regarding how much, how, and when they can occur so that preventive measures can be taken to combat waste.

3. What are the improvement propositions for the analyzed wastes?

Answer: Table 7 demonstrates the applied improvements and suggestions for the sustainability of the Lean Healthcare philosophy in ECU. The improvement propositions were listed according to the reality faced by ECU through the initial diagnosis responses to reduce and/or eliminate the described wastes (Table 1).

Table 7 - Improvement proposals for waste

1. Processing/Creativity - Assess the level of Management/Leadership for a Lean environment
✓ Evidenced leadership involvement, follow-up, and support on a day-to-day basis;
✓ Evidenced that the team has openness to opine and give ideas; management is very close;
✓ Not evidenced suggestion boxes scattered around the unit;
✓ Few processes are defined/officialized (SOP, protocol, etc);
✓ Evidenced excessive communication notices and no standardization;
✓ Not evidenced a visual management chart with the main indicators of the areas;
✓ The use of *Kanban* was not evidenced.

New Lean Healthcare Practices: Application of the See and Act methodology for the team: when the identified problem has a known cause, to be quickly corrected, without major efforts and investments, not causing major damage to the process. Creation of a prototype of a sight management board for the hypodermic room, aiming to facilitate the self-management of the demand by the own employees of the area, besides generating visibility for the management and patients. Once validated by the sector's team, the ECU will provide a definitive/official model. Definition of a standard identification label for drawers, cabinets, etc. This way, professionals will save time when looking for medication or consumable material. Creation of a spreadsheet to control the expiration date of items.
2. Defects - Evaluate the level of adherence to communication and interaction among the team
✓ There are no formal meetings;
✓Information alignments via messaging app are perceived as effective, but informal and without an action plan;
✓Shift changes occur with records (book, forms).
New Lean Healthcare Practices: It was suggested to implement Huddle meetings in the ECU, starting from the management team (board + management) and proceeding to the departmental level, thus creating "top-down" decision making structure. The main objective of this routine is to guarantee the alignment of priorities, problems and improvements. The frequency would be daily, and each meeting would have a maximum duration of 15 minutes. Defining lunch time for each team/sector, aiming at a flow in the cafeteria and avoiding congestion of people in the hallway. Training of the whole unit's team on humanization principles, to avoid addressing the patient by "next" instead of calling him/her by name.
3. Waiting/Inventory - Evaluate the management level through indicators
✓ There are no formal indicators in the unit;
✓ Information is basically based on day-to-day perceptions;
✓ Some actions and improvements are not yet evidenced/recorded.
New Lean Healthcare Practices: Suggestions for process indicators: Cycle and wait times for each of the phases of patient flow (critical path); and Monthly satisfaction survey regarding the length and quality of care provided.
4. Overproduction - Evaluate the level of physical and technological structure
✓ The unit has a large, new structure, is clean and organized in general, but does not use the 5S methodology;
✓ The equipment is working properly;
✓ The layout is good, although there are many patient escorts/family members present;
✓ Manual system of care in general, including charts, medical records, etc;
✓ Evidence of some isolated visual management practices (A4 sheets scattered on bulletin boards, standard identification at the access to rooms).
New Lean Healthcare Practices: The unit is being computerized, with installation of computers in risk classification, offices, medication room, etc; Implantation of 5S events
5. Transportation/Moving - Evaluate if the processes are clear and well defined
✓ Fast track is not deployed in the 24h ECU;
✓ There are no restrictions on the deployment of fast track;
✓ There is no visible process map of the ECU;
✓ The team knows the process flow of the ECU.
New Lean Healthcare Practices: Proposed layout change

Source: ECU INTERNAL REPORTS (2022).

The new lean practices regarding the waste of Overproduction were related to computerization and organization through the implementation of 5S. It is worth mentioning that the 5S tool is a methodology that helps companies of any size and industry to restructure their work methods and standardize their activities. The acronym 5S (*Seiton*, *Seiri*, *Seiso*, *Seiketsu* and *Shitsuke*) comes from five Japanese words starting with the letter S (DENNIS, 2008). This tool has the "S" for sense, namely: sense of use, organization, cleanliness, standardization, and discipline, in this case, within the unit.

Figure 2 - 5S implementation in the warehouse sector

Source: ECU INTERNAL REPORTS (2022).

The warehouse sector was organized, cleaned, and standardized using the 5S senses.

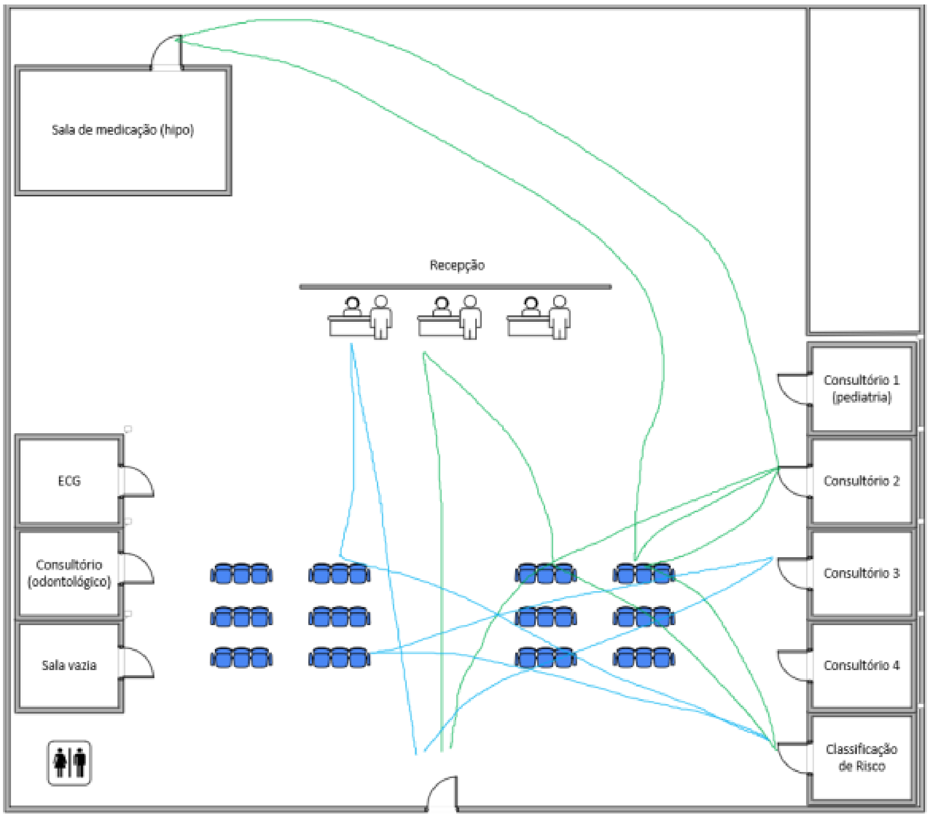
Figure 3 - 5S in the pharmacy

Source: ECU INTERNAL REPORTS (2022).

The pharmacy cabinet that accommodated the health unit's medicines before and after the implementation of the 5S event in the sector. It is worth noting that this improvement was developed by the team operating in the sector.

Similarly, the new lean practices for Transportation/Waste Movement suggest changing the layout of the room, creating a "U" flow, with the chairs facing the reception desk (for waiting for classification or medical care) and on the side, the chairs for waiting for medical discharge and test results (facing the ECG room).

Figure 3 - Proposed layout change



Source: ECU INTERNAL REPORTS (2022).

The empty room (flow layout) was suggested to be transformed into a discharge office, seeking to reduce waiting time. With this action, there will be the separation of 2 patient flows: those in process for 1 consultation on the right-side x those in process for medical discharge on the left side. It should be noted that the HFMEA-Fuzzy modeling was developed prior to the improvements and suggestions presented to the ECU. This modeling was designed to evaluate what were the main wastes found in the ECU under study.

Discoveries

1 - Comparison of two methods: the HFMEA evaluation presented a result, and the HFMEA-Fuzzy modeling provided another result. Through the RPN, the HFMEA method presented the waste of Defects, Waiting/Inventory and Transportation/Movement, respectively. However, the HFMEA-Fuzzy modeling hierarchized the main wastes, also by the RPN technique, respectively: Processing/Creativity and Defects. In this case, the result of the HFMEA-Fuzzy modeling will be considered assertive since it removes from the evaluation the human subjectivities that could affect the result. And this information can be corroborated with Table 6. In Table 6, the main improvement changes were active on these two wastes.

2 - Identification of critical processes: the HFMEA-Fuzzy methodology identified critical processes and failure points through the analysis of the eight wastes (Table 1).

3 - Suggestions from experts: the Demand Matrix (Table 4) identified that, among the five factors, from the perspective of the experts, the two main ones are "adherence to communication and interaction between the team" and "physical and technological structure." According to lean experts, these two factors are important because any institution needs adherent communication, interaction between teams, and a work environment with adequate physical and technological structure to provide smooth services by the institution.

4 - Process safety improvement: the HFMEA-Fuzzy modeling can contribute in various areas, including industry, healthcare, aviation and others, to evaluate and reduce risks in complex systems. This can lead to increased process and product safety, reducing the risk of failures and accidents.

5 - Methodology robustness evaluation: the simulation of the HFMEA-Fuzzy modeling evaluated the methodology's ability to produce accurate and reliable results compared to HFMEA.

6 - Result prediction: the simulation helped researchers predict the main wastes. For this reason, the HFMEA-Fuzzy modeling allows researchers to test different scenarios and hypotheses without the risks and costs associated with conducting real experiments.

Implications practices of the study

Practical implications of HFMEA-Fuzzy modeling for evaluating the eight wastes include:

- Combination of two techniques: the HFMEA-Fuzzy modeling combines two techniques, Failure Mode and Effects Analysis (FMEA) and Fuzzy Logic, which are not typically used together. This combination allows for a more precise and comprehensive analysis of the risks associated with a process or system.
- Systematic approach: the HFMEA-Fuzzy methodology follows a systematic and structured approach to identify the failure modes and their effects on a process or system, based on occurrence, severity and detection criteria. This allows for the identification of critical points in the process or system and the establishment of preventive and corrective measures to mitigate the risks.
- Consideration of uncertainties: Fuzzy Logic, used in the HFMEA-Fuzzy methodology, allows for the mathematical representation of imprecise and subjective variables. This means that the methodology takes into account the inherent uncertainty in health systems and processes and allows this uncertainty to be treated in a systematic and structured way.
- Adaptability: the HFMEA-Fuzzy methodology can be adapted to different healthcare contexts and situations, allowing it to be applied in a wide range of processes and systems. This makes it a valuable tool for risk management in healthcare.

In summary, the HFMEA-Fuzzy methodology is innovative because it combines different techniques, adopts a systematic approach, considers the inherent uncertainty in health systems and processes, and is adaptable to different contexts and situations. All of this contributes to a more precise and comprehensive analysis of risks in healthcare and the definition of effective preventive and corrective measures.

Contribution to the knowledge area

The HFMEA-Fuzzy modeling is an approach that combines the HFMEA method as a basis to identify failure modes and their effects, and then applies Fuzzy Logic to evaluate uncertainties in processes and the overall system. The contribution of this approach to academia and society can be evaluated in various ways.

For academia, the HFMEA-Fuzzy modeling can provide new perspectives and tools for risk analysis in complex systems. This can help improve understanding of how human errors and other factors contribute to incidents and accidents in different sectors. In addition, the HFMEA-Fuzzy modeling can provide a foundation for future research seeking to advance understanding and management of risks.

For society, the HFMEA-Fuzzy modeling can have several practical implications. For example, the approach can be applied in critical sectors such as aviation, healthcare, and industry to assess and manage risks associated with human failures and other sources of uncertainty. This can help improve the safety and reliability of these systems, reducing the risk of accidents and damage to people and property. Additionally, HFMEA-Fuzzy modeling can be applied in other sectors, such as finance and business, to assess and manage risks associated with uncertainties and monetary variations. Overall, this modeling can assist companies and organizations in making more informed decisions and implementing more effective risk management measures.

Conclusion

Based on the use of HFMEA-Fuzzy modeling to assess the eight lean wastes, we can conclude that this approach was successful in identifying critical processes and areas for improvement in an Emergency Care Unit (ECU) in Rio de Janeiro. From the analysis of the data obtained in the simulation, it was possible to identify the main lean wastes for improving the efficiency of ECU processes. This study acquired six new findings from the HFMEA-Fuzzy modeling, and one of the main discoveries was the comparison between the HFMEA evaluation and the HFMEA-Fuzzy modeling, which provided a different result.

The main wastes evaluated by the HFMEA-Fuzzy modeling were, respectively: Processing/Creativity, Defects, Waiting/Inventory and Overproduction, and finally, Transportation/Movement. In addition, through the FUZZY AVERAGE INDEX, it was possible to observe that, considering the practices adopted in the ECU, with no implementation of improvements, an average of 52% of these wastes are frequent, and 76% of them cause significant damage to the system, triggering other wastes. Furthermore, the failure perception is over 100%, meaning that failures are mostly detected.

This study also aims to present the Lean Healthcare philosophy, which has as its main objective the elimination of waste and the maximization of value for the user. It also reinforces the importance of promoting health through continuous education of professionals who work directly in the processes and projects of the ECU. Therefore, new research needs to be conducted in this context in order to increase knowledge about this reality. This document can be of great value for professionals in the field or related areas to generate learning, investigation, and/or implementation of continuous improvement through the eight wastes; for professionals who use Fuzzy logic; and for the HFMEA method for risk management in the healthcare sector in order to improve patient safety.

In summary, the use of this computational modeling for data simulation allowed for the evaluation of different scenarios. Therefore, according to the results obtained, the HFMEA-Fuzzy modeling can be applied in critical sectors such as aviation, healthcare, and industry to assess and manage risks associated with human error and other sources of uncertainty. For this reason, this modeling aims to serve as a stimulus for advances in research on new methods and techniques for risk management in complex systems.

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