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INFANT INCUBATOR DESIGN USING ERGONOMIC FUNCTION DEPLOYMENT (EFD) METHOD TO IMPROVE COMFORT AND EFFECTIVENESS OF NEONATAL CARE

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Abstrak

This study aims to optimize the ergonomic design of an infant incubator using the Ergonomic Function Deployment (EFD) approach to improve the comfort and effectiveness of neonatal care in the neonatal intensive care unit (NICU). An infant incubator is an essential device that provides a stable and controlled environment for premature infants or those with medical conditions requiring intensive care. Key issues examined include infant comfort in the incubator, accessibility and ease of use for healthcare professionals, and efficiency of the control system and interface. Current incubator designs often do not fully consider these ergonomic aspects, which can negatively impact clinical outcomes and the experience of neonatal care. This study will use the EFD method to identify ergonomic needs from the perspective of the infant and healthcare professionals. The research methods used will include evaluation of current incubator designs, data collection from potential users (including infants and healthcare professionals), and analysis to identify existing ergonomic issues. The results of this study recommend technical features such as accurate digital temperature sensors, hypoallergenic materials, visual and audio alarm systems, diffusers for air ventilation, adjustable lighting, HEPA filters to maintain air quality, and ergonomic and easily accessible incubator dimension designs.

Keywords: *Infant Incubator; Ergonomic Function Deployment (EFD); Neonatal; Infant comfort and ENASE*

1. Introduction

Neonatal mortality remains a global challenge, particularly in premature births (World Health Organization, 2023). Ergonomic improvements in incubators can enhance neonatal survival and care outcomes. Previous studies, such as Fernández-Zacarías et al., (2022) and Çetin & Ekici, (2023), focused on environmental control but lacked user-centered ergonomic design integration. This research distinguishes itself by systematically applying the Ergonomic Function Deployment (EFD) method, specifically tailoring incubator design based on detailed ergonomic needs assessment of both infants and healthcare providers. Commercial incubators generally prioritize temperature and humidity regulation, whereas our design prioritizes holistic ergonomics: infant comfort, caregiver accessibility, and user-friendly interfaces.

A baby incubator is a very important tool in the neonatal intensive care unit (NICU) (Kholiq et al., 2024)(Fernández-Zacarías et al., 2022) (Cetin & Ekici, 2023). This device is designed to create an environment like the mother's womb, helping babies born prematurely or with certain medical conditions to develop in optimal conditions. Incubators provide protection by maintaining stable temperature, humidity, and oxygen levels (Mishra et al., 2024). However, although incubator technology has advanced rapidly, there are still a number of ergonomic issues that require special attention (Arianto & Siswoyo, 2022).

Currently, incubator designs often neglect aspects of infant comfort and ease of use for medical

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personnel. Incubators that are not ergonomic can cause various problems. For example, babies who are placed in uncomfortable positions can experience sleep disorders and suboptimal physical development. In addition, medical personnel often face difficulties in accessing and operating incubators, especially in emergency situations. These difficulties can slow down the response to critical situations and increase the risk of medical errors.

Another ergonomic issue is the limited space inside the incubator and the mobility of the device (Bora & Jama, 2020). Limited space makes infant care less efficient and can interfere with the work process of medical personnel. In addition, the difficulty in moving the incubator from one place to another can increase the workload and increase the risk of injury to medical personnel (Kurimoto et al., 2022). The control systems and interfaces on incubators are also often non-intuitive, meaning that medical personnel must spend more time understanding and operating the device, which can increase cognitive load (Kadirova et al., 2022).

The impact of these ergonomic problems is significant (Le Guillou et al., 2023) (Hanafie et al., 2022) (Bentley et al., 2021) (Yparraguirre et al., 2023). The discomfort of the baby in the incubator can affect the quality of his sleep, which is very important for growth and recovery. In addition, difficult access for medical personnel can affect the quality of care and the efficiency of the work of medical personnel, which in turn can affect the clinical outcomes of the baby being treated. Difficulty in using the control system can also lead to human error, which can potentially endanger the health and safety of the baby.

In this context, an ergonomic approach in incubator design becomes very important. This approach aims to ensure that the device is not only functionally effective, but also comfortable and safe for the baby and medical personnel. One method that can be used to integrate ergonomic principles in product design is Ergonomic Function Deployment (EFD) (Bora, Herman, et al., 2023) (Lawi et al., 2023) (Wibowo et al., 2018). EFD is a systematic approach that helps in translating user needs and desires into implementable design specifications (Ahmady et al., 2020) (Safira et al., 2022). EFD was developed from the Quality Function Deployment (QFD) method, which was originally used in quality management, but EFD focuses more on ergonomic aspects and user needs in product design (Bora, Prasetyo, et al., 2023) (Hahury et al., 2023) .

Through the EFD method (Munir & Jakaria, nd) (McConnellsburg, 2020), ergonomic needs from both the infant and the healthcare provider perspective can be identified and analyzed. Furthermore, design solutions that meet these needs can be developed. In the context of infant incubators, EFD can help develop designs that take into account the natural posture and comfort of the infant, provide better access for healthcare providers, and simplify the control system to reduce cognitive load (Nunes, 2022).

This study will examine current infant incubator designs and identify areas for improvement from an ergonomics perspective (Hahury et al., 2023). Through ergonomic analysis using the EFD method, this study will develop design recommendations aimed at improving infant comfort, ease of access for medical personnel, and overall effectiveness of neonatal care. This approach is expected to produce more ergonomic design recommendations, which in turn can improve the quality of neonatal care and clinical outcomes for premature infants. By using the EFD method, this study is also expected to make a significant contribution to the development of more comfortable, safe, and effective infant incubators.

2. Method

2.1 Time and Place of Research

This research will be conducted from July to September 2024 in Batam City, Riau Islands.

2.2 Types of research

The type of research used in this study is quantitative research. Qualitative research is a type of in-depth research to understand phenomena or problems from a complex and detailed perspective (Barella et al., 2024) (Ghanad, 2023) (Disman et al., 2017). This approach focuses more on the interpretation and understanding of the meaning given by participants in a particular context. The main purpose of qualitative research is to explain, describe, and reveal the complexity of the phenomenon being studied.

Qualitative research will be used to explore in-depth the views and experiences of physicians, nurses, and parents of premature infants regarding infant incubator design. This approach allows researchers to explore complex and multidimensional aspects of their perceptions of incubator design, as well as to identify needs, preferences, and challenges that need to be addressed in developing improved ergonomic concepts. Thus, qualitative research in this context will strengthen the understanding of how infant incubator design can be improved to enhance comfort, safety, and efficiency of care in the NICU environment.

2.3 Data collection technique

The data collection techniques used in this study are (Mazhar, 2021)(Klingebiel et al., 2024):

1. Observation: This activity is through NICU observation to understand the care process and interactions between babies, medical personnel, and existing medical equipment. Recording observations related to current incubator use, challenges faced, and potential areas for improvement.
2. Questionnaire and Interview: Distributing structured questionnaires and in-depth interviews to identify existing problems and expectations for the new design. The questionnaires and interviews involved 20 medical personnel (5 doctors, 15 nurses) and 10 infant families to understand the needs and expectations for the incubator design.
3. Literature Study: Conducting a literature study to collect information from research, scientific

journals, books, and other reliable sources related to the research being conducted.

2.4 Data Processing and Analysis Methods

The data processing and analysis method used in this study uses the Ergonomic Function Deployment (EFD) Method. The following are the EFD stages that will be used in data processing and analysis (Pradani et al., 2019) (Liansari et al., 2018):

1. Consumer Needs
The first stage in EFD is to identify and deeply understand the needs of consumers or end users. This includes aspects such as preferences, expectations, and challenges faced by users related to the product or system being developed.
2. Importance of Customer Value
Once consumer needs are identified, the next step is to assess the level of importance or priority of each need to the user. This helps in setting the focus and giving proper weight in product or system development.
3. User Satisfaction Level
This evaluation was conducted to understand the extent to which current user needs and expectations are met by the existing product or system. This level of satisfaction is a reference for identifying areas that need to be fixed or improved.
4. Determining Goal Values
Goal Value refers to the performance target or standard to be achieved in developing a product or system. This goal is set based on an analysis of user needs and interests to ensure that the product design meets the desired expectations.
5. Improvement Ratio Value
Improvement Ratio measures the comparison between the current level of satisfaction and the level of satisfaction expected after the improvement or enhancement is made. This helps in determining the priority of improvements that need to be made to increase user satisfaction.
6. Determining Sales Point Value
Sales Point is a point or aspect of a product that is a selling point or main advantage that is attractive to users. Determining Sales Point is based on an analysis of user needs and expectations to ensure the product has significantly added value.
7. Technical Response
Technical Response refers to the technical characteristics or specifications of a product or system designed to meet user needs. This includes the technical features that will be implemented in the product design.
8. Correlation of User Needs with Technical Response
This stage directly connects the user's needs or preferences with the technical responses provided by the product or system. This correlation is important to ensure that each technical feature or characteristic effectively meets the user's needs.
9. Relationship Between Technical Response (How's)
This relationship illustrates how each technical response or product feature is interrelated and contributes to meeting the overall user needs. This helps in optimizing the product design holistically.
10. Determining Product Specification Targets
Product Specification Target refers to the performance standards or parameters established based on requirements analysis and technical responses. It helps in measuring and evaluating the performance of a product or system during the development and implementation phases.
11. House of Ergonomics (HoE)
HoE is a framework or model used to integrate ergonomic principles into product or system design. It covers aspects such as comfort, safety, and efficiency of use that should be considered in product development.
12. Product Design

The final stage is to implement all the results of the EFD process into a concrete product design. This design must thoroughly consider the identified ergonomic and technical needs to ensure the final product meets user expectations.

3. Results and Discussion

In this study, data processing uses Ergonomic Function Deployment (EFD) by building a matrix called the House of Ergonomics (HoE). HoE is a visual and analytical tool like the House of Quality (HoQ) in the Quality Function Deployment (QFD) method. HoE is used to connect user ergonomic needs with the technical specifications of the designed product. The following are the stages in building the HoE matrix:

a) Identify User Needs

The first stage in EFD is the identification of user needs, which is done through data collection with a questionnaire. These user needs include various aspects of ergonomics, namely Effective, Comfortable, Safe, Healthy and Efficient (ENASE). The following is an explanation of the Ergonomics aspects known by the acronym ENASE in the incubator:

1. Effectiveness: The aspect of effectiveness in ergonomics relates to the ability of the incubator to consistently fulfill its function, namely maintaining the environmental stability required by premature infants or those with certain medical conditions.
2. Comfort: The comfort aspect in the ergonomic design of an incubator includes comfort for the baby inside the incubator, as well as ease and convenience for the medical personnel using it.
3. Safety: Safety is a critical aspect of incubator design to protect vulnerable babies and ensure that the equipment does not pose additional risks.
4. Health: The health aspect of ergonomics focuses on ensuring that the incubator environment supports the health of the baby and does not cause long-term negative effects.
5. Efficiency: Efficiency in the context of ergonomics relates to the ability of the incubator to be used optimally without burdening medical personnel and by reducing the time and effort required for operation.

Table 1. Summary of Data Results on the Level of Interest

No	User Requirements	STP	TP	CP	P	SP	Value of Interest
1.	Precise temperature control to maintain baby's stability	3	5	7	8	7	3.37
2.	Soft and hypoallergenic bedding material	5	7	4	10	4	3.03
3.	Alarm system that is sensitive to changes in critical conditions	7	7	1	8	7	3.03
4.	Good ventilation system without direct exposure to the baby	8	5	10	3	4	2.67
5.	Lighting that can be adjusted according to the baby's needs	2	4	5	11	8	3.63
6.	High quality air filtration system for clean water	4	6	8	7	5	3.20
7.	The ideal dimensions of a baby incubator make it easy for medical personnel to move it.	6	5	9	5	5	2.97
8.	Ease of access for cleaning and sterilization	5	6	6	7	6	3.10

Note: 1: Very Unimportant - This need is not important to me at all.
2: Not Important - This need is less important to me.
3: Quite Important - This need is important, but not a top priority.
4: Important - This need is very important and must be met.
5: Very Important - This need is very critical and is a top priority.

Table 2. Target Value (Goal), Improvement Ratio Value, Determination of Sales Point Value, Raw Weight, and Normalized Raw Weight and Priority

No	User Requirements	Target	IR	SP	*RW*	*NRW*	Priority
1	Precise temperature control to maintain baby's stability	5	1.48	1.5	7.48	0.169	2
2	Soft and hypoallergenic bedding material	4	1.32	1.2	4.80	0.109	4
3	Alarm system that is sensitive to changes in critical conditions	5	1.65	1.5	7.50	0.170	1
4	Good ventilation system without direct exposure to the baby	4	1.50	1.2	4.81	0.109	5
5	Lighting that can be adjusted according to the baby's needs	4	1.10	1.2	4.79	0.108	7
6	High quality air filtration system for clean water	4	1.25	1.5	6.00	0.136	3
7	The ideal dimensions of a baby incubator make it easy for medical personnel to move it.	4	1.35	1.0	4.01	0.091	8
8	Ease of access for cleaning and sterilization	4	1.29	1.2	4.80	0.109	6

b) Importance of Customer Value

Once user needs are identified through ergonomic needs analysis, the next step is to determine the level of importance or priority of each need. This level of importance is the result of a survey or interview with users, where they were asked to rate how important each ergonomic need is to the ENASE aspect of using a baby incubator. The results of the Importance to Customer (ITC) Assessment using a Likert scale of 1-5 can be seen in **Table 1**.

c) Determination of Target (Goal), Improvement Ratio, Sales Point, Raw Weight, Normalized Raw Weight and Priorities

Goal Value is a performance target designed to achieve optimal standards in the development of a new infant incubator, in accordance with the primary needs of users, namely infants and medical personnel in the neonatal intensive care unit (NICU). This target is set on an analysis of user needs that have been prioritized using a Likert scale of 1-5, thus reflecting the focus of the design on the most urgent aspects to be improved. To support the achievement of the Goal Value, the Improvement Ratio is used, which is a comparison between the current level of satisfaction and the expected satisfaction after improvements are made. This value is a critical measuring tool that provides an overview of the extent to which improvements are needed. For example, the aspect of precise temperature control shows a high Improvement Ratio, underlining the need for significant innovation in this feature. In addition, Sales Point is an important element that identifies the main aspects of the product that are attractive to users. Features such as a sensitive alarm system for critical conditions and hypoallergenic materials are some of the main selling points resulting from the analysis of user needs. Determining Sales Point ensures that the incubator not only meets technical needs but also has competitive advantages that are relevant to user expectations. In the prioritization process, Raw Weight is used as an indicator of the overall level of importance of each need. This value is calculated by multiplying the level of importance, Improvement Ratio, and Sales Point. The higher the Raw Weight value, the more critical the need is to be met. For example, stable temperature control has the highest Raw Weight, confirming its urgency in the design. The Raw Weight value is then processed into a Normalized Raw Weight to represent the priority weight on a scale of 0–1. This process makes it easier for developers to understand the proportion of user needs relative to the overall design, so that focus can be given to elements that have the greatest impact, such as alarm systems and air filtration. Based on the results of this analysis, development priorities are determined to ensure that the most significant user needs are met first. This structured approach not only ensures that the infant incubator design meets the expected performance standards, but also provides greater comfort, safety, and effectiveness for infants and medical personnel in the NICU environment. Thus, the final design can be expected to be a comprehensive solution in improving the quality of neonatal care. The result of Determination of Target (Goal), Improvement Ratio, Sales Point, Raw Weight, Normalized Raw Weight and Priorities can be seen in **Table 2**.

Table 3. Technical Response

No	User Requirements	Technical Response
1.	Precise temperature control to maintain baby's stability	Digital temperature sensor with an accuracy of ±0.1°C, ensures the temperature remains stable according to the baby's needs.
2.	Soft and hypoallergenic bedding material	Hypoallergenic materials such as polyurethane foam covered with anti-bacterial and anti-fungal medical fabric. Length 60 cm, width 40 cm and thickness 5 cm
3.	Alarm system that is sensitive to changes in critical conditions	Audio and visual alarm with sound intensity of 70-80 dB Detects changes in temperature and oxygen levels with a latency of no more than 2 seconds.
4.	Good ventilation system without direct exposure to the baby	Air flow capacity 10-15 L/min Closed ventilation with an air diffuser ensures gentle and indirect airflow to the baby.
5.	Lighting that can be adjusted according to the baby's needs	Warm white light with a color temperature of 4000K, which resembles natural light for baby's comfort.
6.	High quality air filtration system for clean water	HEPA (High-Efficiency Particulate Air) filter and activated carbon filter, double layered, to ensure clean air.
7.	The ideal dimensions of a baby incubator make it easy for medical personnel to move it.	The size of the baby incubator is 65 cm (w) x 45 cm (w) x 42 cm (h).
8.	Ease of access for cleaning and sterilization	Removable components for cleaning and sterilization, with disassembly time less than 5 minutes. Fully retractable side and top panels

Table 4. Relationship between User Needs and Technical Response

User Requirements \ Technical Response	Digital temperature sensor with accuracy of ±0.1°C	Hypoallergenic material	Bed Size (60 cm x 40 cm x 5 cm)	Audio and visual alarm with sound intensity of 70-80 dB	Detect changes in temperature and oxygen levels with a latency of no more than 2 seconds.	Air flow capacity 10-15 L/min	Closed ventilation with air diffuser	Warm white light with a color temperature of 4000K	HEPA (High-Efficiency Particulate Air) Filter	The size of the baby incubator is 65 cm (w) x 45 cm (w) x 42 cm (h).	Removable components	Fully retractable side and top panels
Precise temperature control to maintain baby's stability	○				●	○	△					
Soft and hypoallergenic bedding material		●	○					△				
Alarm system that is sensitive to changes in critical conditions				●	●	△						
Good ventilation system without direct exposure to the baby						●	○			△		
Lighting that can be adjusted according to the baby's needs								●		△	△	
High quality air filtration system for clean air									●			
The ideal dimensions of a baby incubator make it easy for medical personnel to move it.										●	○	△
Ease of access for cleaning and sterilization											●	●

d) Technical Response

Technical Response refers to the technical characteristics or specifications of the infant incubator designed to meet the needs of the user. Each ergonomic need is translated into technical specifications that can be implemented in the product design. **Table 3** shows the technical characteristics of the infant incubator.

e) Correlation of User Needs with Technical Response

This stage involves directly linking the identified user needs to the technical responses implemented. This correlation ensures that each technical specification effectively meets the ergonomic needs of the user. A relationship matrix is a matrix created to show the relationship between user needs and technical responses. These relationships are weighed or scored to assess the extent to which the technical specifications meet the user's needs. This relationship can be seen in **Table 4**.

f) Relationship Between Technical Response (How's)

This relationship illustrates how each technical response or product feature is interrelated and contributes to the overall satisfaction of user needs. This relationship helps in optimizing the product design holistically. This relationship can be seen in **Figure 1**.

g) Determining Product Specification Targets

Product Specification Targets are performance standards or parameters that are set based on needs analysis and technical responses. These targets are used to measure and evaluate product performance during the development and implementation phases. Product specification targets can be seen in **Table 5**.

h) House of Ergonomic (HoE)

House of Ergonomics (HoE) is a framework that integrates ergonomic principles into the design of infant incubators. HoE includes elements such as comfort, safety, and efficiency of use, and links them to the technical aspects of the product.

The findings align with ergonomic principles such as 'posture and movement optimization', 'cognitive ergonomics' in alarm designs, and 'environmental ergonomics' related to air quality and lighting. Each technical specification was crafted not only for functionality but also for minimizing cognitive load, enhancing access, and reducing risks of musculoskeletal disorders among caregivers. House of Ergonomic can be seen ini **Figure 2**.

4. Conclusion

Based on the research that has been conducted, the following conclusions can be drawn:

1. This study successfully identified the main ergonomic needs that are not fully met in current infant incubators through Ergonomic Function Deployment (EFD) analysis. By collecting data from medical personnel and assessing the needs of infants in the NICU, several aspects were found that needed improvement, such as more precise temperature settings, the use of hypoallergenic materials, a fast and sensitive alarm system, indirect air ventilation, adjustable lighting , and a quality air filtration system. Each of these needs was prioritized based on the level of importance and user satisfaction, as well as the potential for improvement to improve infant comfort and safety.
2. This study has developed recommendations for infant incubator designs that integrate ergonomic principles with the EFD method. This process

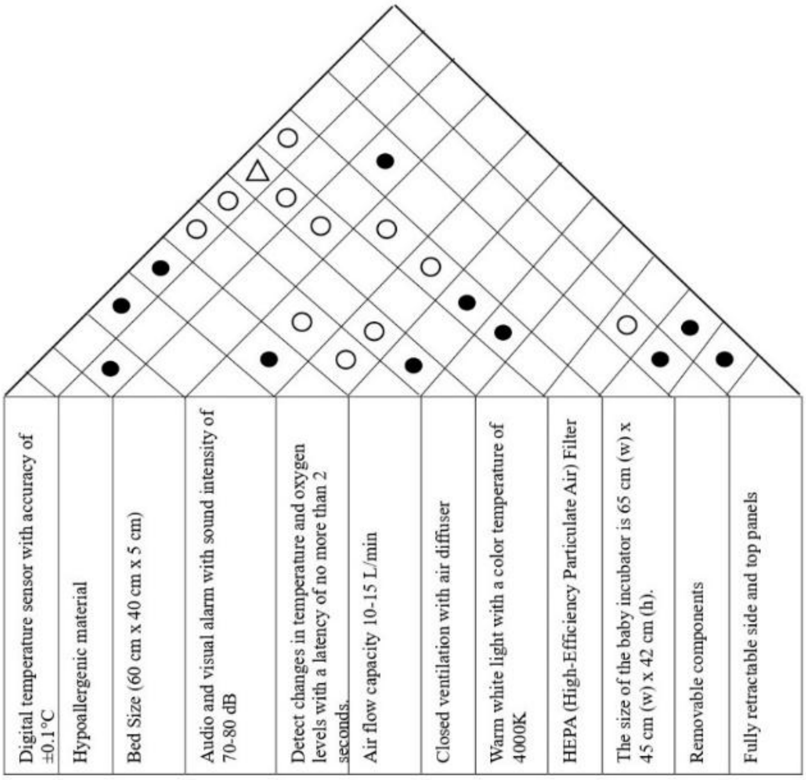

Figure 1. Relationship between Technical Responses

Table 5. Target Product Specification

No	Technical Aspects	Target Product Specification
1.	Digital temperature sensor with accuracy of ±0.1°C	Temperature accuracy reaches ±0.1°C to maintain a stable temperature in the range of 36-37°C, with a response time of less than 2 seconds.
2.	Hypoallergenic material	Hypoallergenic, anti-bacterial and anti-fungal material, with a soft surface that meets ISO 10993 medical standards for direct contact.
3.	Bed Size (60 cm x 40 cm x 5 cm)	Bed dimensions: length 60 cm, width 40 cm, thickness 5 cm; supports baby weight up to 5 kg without material deformation.
4.	Audio and visual alarm with sound intensity of 70-80 dB	Visual and audio alarms with sound intensity between 70-80 dB that activate in less than 2 seconds when a critical condition change is detected.
5.	Detect changes in temperature and oxygen levels with a latency of no more than 2 seconds.	Temperature and oxygen detection response with a maximum latency of 2 seconds, integrated with automatic alarm.
6.	Air flow capacity 10-15 L/min	Steady airflow of between 10-15 L/min, at low speed to maintain direct airless circulation to the baby.
7.	Closed ventilation with air diffuser	Diffuser that maintains even air circulation, indirect flow to the baby, maintaining humidity and oxygenation within optimal limits.
8.	Warm white light with a colour temperature of 4000K	4000K warm lighting with adjustable lighting intensity between 0-300 lux for the comfort of babies and medical personnel.
9.	HEPA (High-Efficiency Particulate Air) Filter	Double HEPA filter with the ability to filter particles up to 0.3 microns with 99.97% efficiency, to maintain air quality inside the incubator.
10.	The size of the baby incubator is 65 cm (w) x 45 cm (w) x 42 cm (h).	The overall dimensions of the incubator are 65 cm x 45 cm x 42 cm, facilitating mobility and access for medical personnel, and is compatible with NICU rooms.
11.	Removable components	The incubator components can be removed in less than 5 minutes for cleaning and sterilization, with a secure click system.
12.	Fully retractable side and top panels	The side and top panels can be opened to 180 degrees for maximum access during baby care, meeting the ergonomic standards of neonatal care.

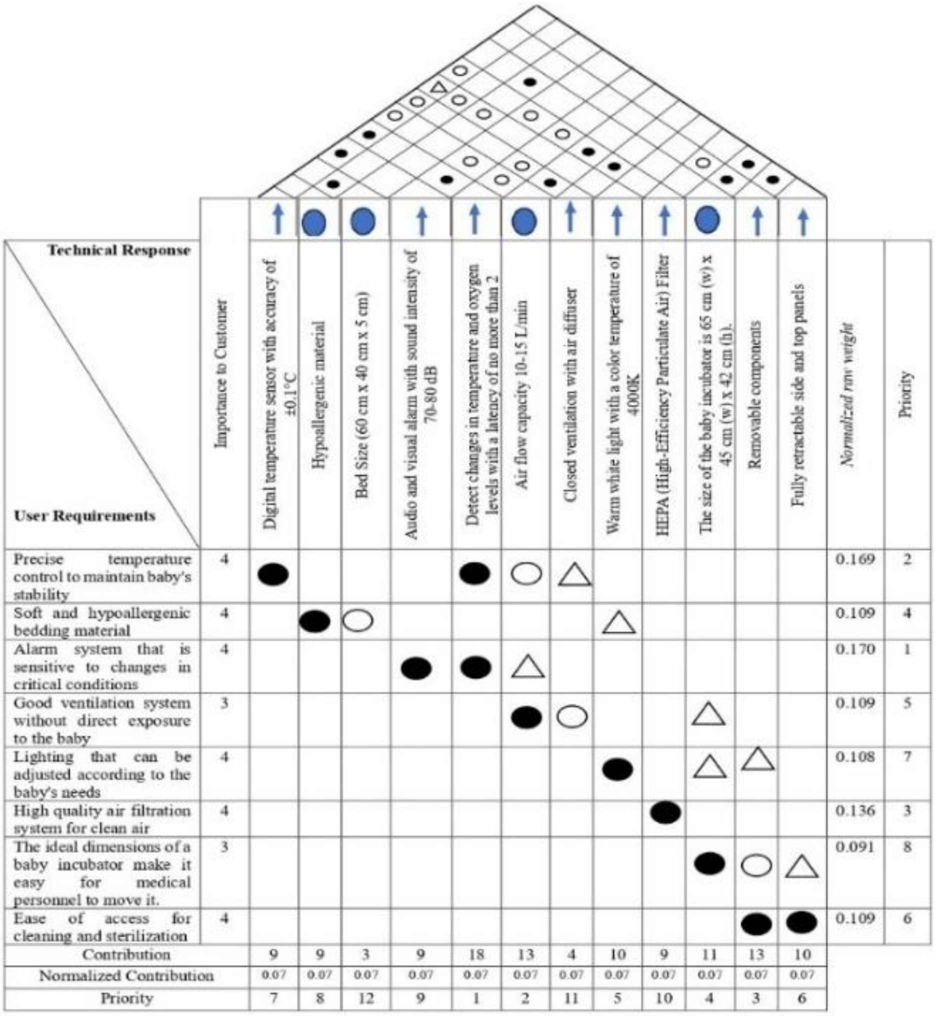

Figure 2. House of Ergonomic

the application of the House of Ergonomics (HoE) to link user needs with specific technical responses. The final recommended design includes technical features such as accurate digital temperature sensors, hypoallergenic materials, visual and audio alarm systems, diffusers for air ventilation, adjustable lighting, HEPA filters to maintain air quality, and ergonomic and accessible incubator dimensions. With this approach, the resulting incubator is expected to be able to meet the needs of infants and medical personnel, thereby increasing the effectiveness of neonatal care in the NICU.

3. This study advances the application of ergonomic engineering in neonatal devices by demonstrating the effective integration of EFD into medical equipment design. It also provides a scalable methodology for future human-centered innovations in the NICU environment.

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