LAUGHING GAS, NO LAUGHING MATTER

ANALYZING THE TECHNICAL, CLINICAL, AND INFRASTRUCTURAL DIMENSIONS OF NITROUS OXIDE FOR A MORE SUSTAINABLE FUTURE.

HANNAH WINDER

MASTER THESIS TECHNICAL MEDICINE

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Laughing gas, no laughing matter

Analyzing the Technical, Clinical, and Infrastructural Dimensions of Nitrous Oxide for a more sustainable future

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Preface and Acknowledgement

This thesis marks the culmination of my Master's studies in Technical Medicine at Delft University of Technology, Erasmus University Rotterdam, and Leiden University. The journey has been both challenging and rewarding, and above all, deeply inspiring. Over the past years, I have had the privilege of exploring the intersection of healthcare, technology, and clinical practice, an area that has fueled my passion for not only improving patient care through innovation but also addressing the urgent challenge of sustainability within the medical field.

Like most of my peers, my academic journey began with the Bachelor's program in Clinical Technology. Alongside my formal education, stepping into various leadership and board roles, from driving sustainable entrepreneurship in the CleanTechChallenge to organizing healthcare innovation programs, broadened my perspective and helped me cultivate skills that complemented my technical training. Transitioning into my Master's specialization in Imaging & Intervention, each phase of this journey has deepened my curiosity and fostered both academic and personal growth. Working on this graduation project at the Leiden University Medical Center (LUMC) has been a defining moment in my studies, allowing me to directly address the climate impact of healthcare by researching the sustainable use of medicinal nitrous oxide within the Departments of Anesthesia and Obstetrics.

I am grateful to my supervisors, Anne van der Eijk, Claar Lap, and Maelle Lustig for their invaluable guidance, expertise, and encouragement throughout this process. Your insights and feedback have challenged me to think critically, balancing the necessity of high-quality patient care with the drive for environmental responsibility. I would also like to thank Jenny Dankelman for taking the time to serve as part of my thesis committee.

To my fellow students and colleagues at the LUMC, thank you for your camaraderie, shared insights, and the many coffee and lunch breaks that provided much-needed moments of reprieve and laughter during my studies.

Finally, I want to express my deepest gratitude to my parents, sister, friends, and roommates. Your unwavering support, patience, and encouragement have been a constant source of motivation. The happy memories we've shared over the years have brought me immense joy and inspiration, reminding me of the solid foundation I am lucky to stand on.

As I conclude this chapter and look toward a future where I hope to help bridge the gap between medical excellence and a smaller climate footprint, I am incredibly excited to apply the lessons learned here to my future professional endeavors.

Hannah Winder

Amsterdam, June 2026

Abstract

Nitrous oxide (N_2O) is a widely used inhalational analgesic and anesthetic across clinical settings including obstetrics, pediatrics, emergency medicine, and dentistry. However, its global warming potential (273 times that of CO_2 over a 100-year horizon) and documented occupational health risks make its unmitigated clinical use increasingly difficult to justify within contemporary sustainability frameworks.

This thesis provides a comprehensive, multi-dimensional evaluation of N_2O management in healthcare, integrating a systematic technology review, an institutional case study at Leiden University Medical Center (LUMC), and a clinical deep-dive into obstetric practice.

Chapter 1 maps the global landscape of N_2O delivery, scavenging, and destruction technologies across a dataset of 60 devices from 19 manufacturers. Findings reveal that 78.3% of catalogued systems provide zero active greenhouse gas mitigation, with true catalytic destruction present in only 11.7% of devices. Significant geopolitical stratification limits technology access in lower-income healthcare systems, while regional regulatory divergence drives fragmented clinical adoption.

Chapter 2 quantifies seven years of institutional N_2O consumption at LUMC (2019–2025), modeling cumulative unmitigated emissions of 103,637 kg CO_2-eq across four departments. The sharpest emissions growth was driven by the 2023 introduction of N_2O-based cryoanalgesia for pediatric pectus excavatum repair. Substantial discrepancies between theoretical and real-world carbon footprints were identified, attributable to point-of-use catalytic destruction systems and infrastructural transitions. Critical regulatory compliance gaps in ambient occupational exposure monitoring were documented.

Chapter 3 analyzes 403 obstetric labor episodes at LUMC. Despite modest objective pain reduction (mean VAS decrease of 1.63 $\pm$ 1.48 points), patient and provider satisfaction scores remained high (7.31 and 7.76 out of 10, respectively), illustrating the well-documented analgesic paradox of N_2O. The overall analgesic conversion rate to epidural or remifentanil analgesia was 18.35%, rising to 25.37% among primiparous patients, supporting risk-stratified clinical routing recommendations.

Collectively, these findings demonstrate that sustainable N_2O governance cannot be achieved through isolated end-of-pipe solutions. Instead, institutions require a coordinated strategy encompassing decentralized cylinder-based supply, workflow-matched abatement technologies, risk-stratified clinical protocols, and governance structures that integrate frontline clinical expertise. The Dutch regulatory framework, combining occupational health law, sustainability covenants, and professional clinical standards, is identified as an instructive model for international healthcare systems seeking to reduce direct anesthetic gas emissions without compromising patient care.

AI Disclosure

Generative artificial intelligence (AI) was used in this thesis only to improve the clarity and structure of the writing. It was not employed for research designs, analysis, interpretation or the development of arguments. These were independently conceived and written by the author.

Contents

General Introduction

Nitrous oxide (N_2O) is a gas widely used across multiple sectors, including healthcare and technical industries [1]. In healthcare, nitrous oxide is primarily applied as an inhalational anesthetic with analgesic and sedative properties [2]. Within clinical settings, it is utilized across a broad range of departments, including anesthesiology, obstetrics, pediatrics, emergency medicine, and dentistry [3, 4, 5, 6, 7].

The climate impact of N_2O is substantial [8]. Nitrous oxide has a global warming potential (GWP) 273 times greater than that of carbon dioxide (CO_2) over a 100-year time horizon, according to the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) [9]. Consequently, when released into the atmosphere, emissions of N_2O contribute disproportionately to global warming compared to an equivalent mass of CO_2 [9]. In addition, N_2O contributes to ozone depletion by reacting with ozone in the stratosphere, leading to thinning of the ozone layer [10]. Changes in the ozone layer can alter atmospheric circulation patterns, including wind patterns, thereby indirectly influencing the climate system [11]. Therefore, limiting the release of N_2O into the atmosphere is essential.

Strategies to limit N_2O emissions can be structured according to the so-called "5R" framework [12]. The first principle is Refuse or Reduce, which focuses on minimizing the use of nitrous oxide, thereby directly reducing potential atmospheric emissions. In addition, Reuse strategies aim to capture nitrous oxide for subsequent reuse, for example through adsorption using metal–organic frameworks (MOFs); however, such technologies are currently insufficiently developed for routine clinical application [13]. Finally, Recycle approaches focus on preventing the release of used N_2O into the atmosphere by chemically decomposing it into nitrogen (N_2) and oxygen (O_2), typically through catalytic destruction processes [14].

In addition to its impact on climate change, N_2O is associated with clinical health risks following prolonged occupational exposure [15]. Historically, nitrous oxide was administered using open or semi-open delivery systems, which resulted in elevated ambient concentrations in clinical environments [16]. Prolonged exposure to nitrous oxide has been associated with adverse reproductive outcomes, including an increased risk of spontaneous abortion, reduced fertility, and potential developmental effects in the fetus [17]. As a result, strict occupational exposure limits and safety regulations have been established to minimize healthcare workers' exposure to nitrous oxide in the workplace [18].

To mitigate climate change and to protect the health of healthcare personnel, it is essential to reduce the release of N_2O into the atmosphere [19]. Within healthcare settings, this can be achieved either by reducing the overall use of nitrous oxide or by improving the capture and destruction of residual gas following clinical administration [19]. Contemporary clinical practice therefore requires the administration of nitrous oxide via closed or low-leakage delivery systems, in combination with effective scavenging systems, to minimize environmental emissions and occupational exposure [20].

To mitigate the environmental footprint of N_2O across institutional healthcare delivery, it is imperative to optimize both the absolute volumetric consumption of the gas and the efficiency of point-of-use waste containment. While systematic reduction in gas utilization minimizes baseline emissions, the ongoing clinical necessity of nitrous oxide across diverse departments, including intrapartum analgesia in labor wards, acute procedural sedation within the Emergency Department (ED), specialized pediatric interventions in the Children's Hospital, and inhalation maintenance or cryoanalgesia frameworks inside Operating Rooms (OR), demands robust scavenging, source-capture, and downstream catalytic destruction architectures to prevent unmitigated release into the biosphere. Because operational parameters vary extensively by clinical department, variations in system capture performance, fugitive pipeline leakages, or suboptimal clinical workflows can directly result in unnecessary greenhouse gas venting and elevated occupational exposure risks for medical personnel.

Therefore, this study aims to provide a comprehensive evaluation of N_2O management by connecting global technical innovations with local clinical practice at Leiden University Medical Center (LUMC). This research evaluates the sustainability and efficiency of current "state of the art" scavenging and degradation technologies, maps the seven-year evolution of N_2O utilization across LUMC, and conducts a clinical deep dive into the obstetric department's analgesic efficacy and conversion rates. By identifying technical and organizational bottlenecks, this study seeks to deliver practical, evidence-based recommendations that balance clinical efficacy, occupational safety, and environmental sustainability.

1 Technical Infrastructure & Sustainability

1.1 Introduction

Nitrous oxide remains a cornerstone of contemporary anesthetic and analgesic practice, favored for its rapid pharmacokinetics and negligible metabolic degradation [21, 22]. However, its clinical deployment is highly heterogeneous across medical specialties [23]. While obstetric departments frequently utilize N_2O for prolonged periods during labor [24], emergency and pediatric departments typically employ it for transient procedural sedation [25]. This divergence in clinical application necessitates a sophisticated technical infrastructure capable of ensuring both patient safety and the mitigation of chronic occupational exposure for healthcare personnel [26, 27].

Regardless of its clinical efficacy, N_2O presents a significant dual challenge. Firstly, stringent occupational health regulations (such as the Dutch *Arbowet*) mandate robust scavenging and ventilation protocols to prevent long-term health risks to staff [28]. Secondly, N_2O is a potent greenhouse gas, possessing a GWP approximately 273 times that of CO_2 over a 100-year horizon [9]. Current mitigation strategies range from rudimentary atmospheric venting to advanced catalytic thermal decomposition (cracking). Nevertheless, there remains a critical lacuna in the literature regarding a systematic evaluation of these technologies based on clinical utility, operational exigencies, and environmental impact. This deficit delays healthcare providers from implementing sustainable and secure N_2O policies tailored to departmental specificities.

The objective of this research is to provide a comprehensive analysis of the "state of the art" in N_2O management within the healthcare sector. This review evaluates administration and abatement technologies within the framework of operational feasibility and environmental stewardship. The central research question is: *"How do current and emerging N_2O management technologies compare in terms of clinical applicability, operational requirements, and their potential to reduce the environmental footprint of healthcare facilities?"*

1.2 Theoretical Framework

The environmental burden of anesthetic gases is quantified via the GWP, which measures the heat-trapping capacity of a gas relative to CO_2 over a 100-year horizon GWP_{100}. According to the IPCC Sixth Assessment Report (AR6), N_2O possesses a GWP of 273 [9]. This metric enables the comparative analysis of various medical gases and their contribution to the hospital's carbon footprint.

The efficiency of nitrous oxide management is fundamentally predicated upon the delivery modality: centralized piped infrastructure versus decentralized mobile cylinders. Evidence suggests that centralized nitrous oxide piping systems are frequently compromised by significant leakages [29]. Studies indicate that, on average, up to 80% of nitrous oxide may be lost to the atmosphere via systemic leaks before reaching the point of care [30]. This not only exacerbates the facility's carbon footprint but also imposes a substantial financial burden. Consequently, a shift is observed in many Dutch clinical settings toward the adoption of mobile cylinders, which minimize transit-related losses.

A second critical determinant of management efficiency occurs at the point of administration. The technical configuration of delivery systems dictates the volume of waste gas generated. The primary distinction lies in the triggering mechanism: continuous-flow systems deliver a constant stream of gas, resulting in significant "over-delivery" and atmospheric wastage. Conversely, demand-flow systems utilize a dedicated valve that activates only during the inspiratory phase. From a sustainability perspective, demand-flow systems serve as a primary intervention; by reducing consumption at the source, they simultaneously diminish procurement costs and the total volume of N_2O requiring subsequent scavenging or cracking [31].

Aligned with the "R-ladder" hierarchy of circularity, the most efficacious strategy is "Refuse", the systematic reduction of N_2O utilization shown in Figure 1. Ideally, the medical sector would transition toward a closed-loop system. Because N_2O undergoes minimal chemical alteration within the human body, it is exhaled in a state nearly identical to its inhaled form [32]. However, the recapture of N_2O presents significant physicochemical challenges. Activated carbon adsorption, which is effective for larger halogenated anaesthetic agents such as sevoflurane and isoflurane, is fundamentally ill-suited for N_2O due to its small molecular size (44 g/mol), negligible polarity, and very low boiling point (−88 °C) [33]. These properties result in weak Van der Waals interactions between N_2O molecules and the carbon surface, causing the gas to pass through the adsorbent without being retained [33]. In clinical settings, this limitation is further compounded by the high moisture content of exhaled breath: water molecules competitively occupy adsorption sites, reducing the already insufficient uptake of N_2O [34]. While activated carbon has been explored in industrial contexts where the gas stream can be dried and pressurised prior to adsorption, even these conditions do not fully overcome the intrinsic molecular limitations of N_2O [34]. The use of Metal-Organic Frameworks (MOFs) represents a promising frontier for gas adsorption; however, despite the recent 2025 Nobel Prize in Chemistry highlighting their potential, MOFs remain in the experimental phase and are not yet viable for widespread clinical implementation [13].

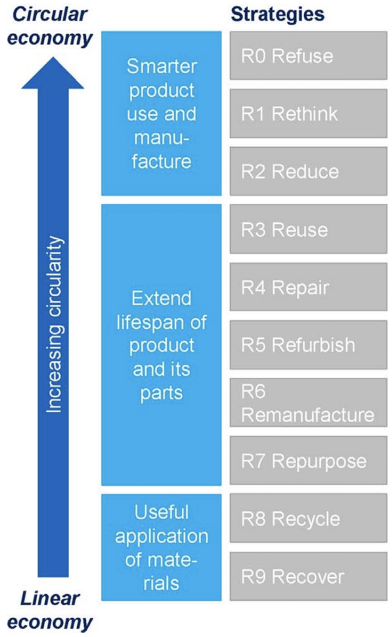

Figure 1: R-ladder [35]

Post-exhalation, N_2O must be captured to preserve ambient air quality. Scavenging systems utilize vacuum pressure to divert exhaled gases away from the clinical environment. While these systems satisfy occupational safety requirements, traditional configurations often vent these gases directly into the atmosphere, failing to address the environmental burden. Finally, cracking refers to the catalytic decomposition of N_2O into nitrogen and oxygen ($2N_2O \rightarrow 2N_2 + O_2$). This review categorizes such abatement into two distinct modalities:

- **Mobile Units:** Optimally suited for departments with fluctuating demand or decentralized spatial layouts (e.g., individual delivery suites).
- **Centralized Units:** Integrated into the facility's primary exhaust infrastructure, providing a high-capacity solution for institutions with high-volume N_2O consumption across multiple wards.

1.3 Methods

This research employs an exploratory, qualitative and quantitative content analysis design to evaluate the current state of the art in medical N_2O management and sedation technologies. The methodology was structured to synthesize data from both established clinical standards and emerging technological innovations, culminating in the construction of a dedicated technology characterization dataset.

1.3.1 Data Sourcing and Dataset Construction

Data were gathered from a diverse range of authoritative sources to ensure a comprehensive overview of the technical, clinical, and environmental landscape. The data retrieval strategy relied on a multi-layered sourcing framework:

- **Clinical and Scientific Literature:** Peer-reviewed scientific literature and clinical guidelines issued by professional medical bodies (e.g., anesthesia and obstetric societies) were reviewed to map regional clinical adoption patterns.
- **Technical and Industry Documentation:** Technical product specifications, user manuals, safety data sheets, and white papers were sourced directly from medical device manufacturers and engineering firms specializing in gas abatement.
- **Regulatory Registries:** Publicly available medical device registries and regulatory filings (e.g., FDA approvals, CE markings) were cross-referenced to verify commercial availability and infrastructure configurations.

1.3.2 Inclusion and Exclusion Criteria

To ensure clinical relevance and data integrity, strict boundaries were established for the device selection process.

Devices were included if they met the following criteria:

1. They are explicitly designed for medical or dental N_2O delivery, scavenging, monitoring, or active climate mitigation.
2. They are currently commercially available or in active clinical trials within the European Union (EU), the United Kingdom, the United States, or Commonwealth jurisdictions (Australia, New Zealand, Canada).
3. Verifiable technical data sheets or peer-reviewed operational profiles were accessible.

Devices were excluded if they were engineered exclusively for industrial, automotive, or non-medical chemical applications, or if insufficient technical data was available to evaluate their environmental or operational parameters.

1.3.3 Variable Extraction and Analytical Framework

For each of the identified systems, data were systematically extracted and coded into a structured database. The variables captured included manufacturer identity, primary clinical department compatibility, underlying functional mechanism, validated greenhouse gas destruction capabilities, lifecycle/maintenance parameters, and the transparency of capital and operational financial data.

The finalized dataset was analyzed using a six-dimensional framework to structure the findings logically:

1. **Market Landscape and Device Identification:** Assessing manufacturer market share, polarization, and niche versus mainstream infrastructure dominance.
2. **Clinical Contextualization and Departmental Mapping:** Classifying device compatibility across clinical departments (e.g., Pediatrics, Dentistry, Obstetrics, Operating Rooms).
3. **Technological Archetypes and Functional Mechanisms:** Categorizing systems based on their operational capabilities, such as delivery, local scavenging, real-time monitoring, physical capture, or active chemical conversion.
4. **Environmental Impact and the Carbon Mitigation Paradox:** Evaluating the operational divergence between local occupational protection (scavenging/displacement) and true global atmospheric mitigation (thermal/catalytic cracking or low-flow recycling).
5. **Lifecycle, Maintenance, and Waste Stream Characteristics:** Analyzing hardware longevity, routine service/calibration burdens, and the systemic generation of single-use medical plastic waste.
6. **Economic Drivers and Data Vulnerabilities:** Mapping qualitative fiscal profiles (CAPEX and OPEX variables) against known data reporting gaps within the medical manufacturing sector.

Cross-tabulation and descriptive frequency distributions were applied to evaluate correlations between technological archetypes and environmental mitigation efficacy.

1.3.4 Case Study Selection and Analytical Framework

To evaluate the operational dynamics, environmental trade-offs, and clinical infrastructure requirements of N_2O management in healthcare facilities, a multi-archetype case study methodology was implemented using the LUMC as the core empirical baseline. The LUMC serves as a highly representative model for exploring systemic medical gas management for several critical reasons. As a prominent tertiary academic medical center, the institution handles highly complex care profiles across a vast array of specialized clinical disciplines, mirroring the multifaceted demands of a large-scale healthcare ecosystem.

Furthermore, the absence of centralized, uniform institutional mandates regarding nitrous oxide procurement and disposal has allowed individual departments to manage their clinical protocols independently. This decentralized governance structure has created diverse practices within a single institution, ranging from standard atmospheric venting to active localized scavenging. Consequently, the LUMC functions as an ideal micro-scale proxy, capturing the procedural variations and infrastructure challenges encountered across the broader national and international healthcare landscape. Based on the systems deployed across these varied departments and available market solutions, the analytical framework is partitioned into two distinct target comparisons.

The first comparison investigates the local infrastructure utilized at LUMC, contrasting the *Medclair AB Mobile Destruction Unit* with the *Puramed Centraal Anaesthetic Gas Scavenging System (AGSS)*. Because the Medclair Mobile Unit is currently the only commercially available decentralized mobile destruction system on the market, direct comparison with an equivalent mobile system was impossible; thus, it was contrasted against a centralized extraction infrastructure to evaluate decentralized cracking versus centralized atmospheric displacement.

The second comparison analyzes facility-scale, end-of-pipe mitigation solutions by evaluating the *Medclair AB Central Destruction Unit (CDU)* against the *MedicVent Nitrous Oxide Destructor DeN2O-S3*. While Medclair engineers a single standardized configuration for centralized destruction, MedicVent produces three distinct centralized destruction units categorized by scale and throughput capacity. To ensure architectural comparability with the Medclair Central CDU, the mid-sized variant from the MedicVent portfolio (the DeN2O-S3) was selected for structural evaluation.

The evaluation framework standardized these systems across six core analytical dimensions: technological mechanism (active catalytic cracking vs. atmospheric displacement), cross-functional clinical deployment, solid lifecycle waste streams (presence of single-use plastic configurations), asset longevity, maintenance intervals, and qualitative expenditure profiles (Capital Expenditure [CAPEX] vs. Operational Expenditure [OPEX]). This dual-archetype configuration allows for a robust assessment of how local occupational safety interventions interact with global institutional carbon-mitigation targets.

1.4 Results

1.4.1 Overview of Global and Regional Clinical Adoption

The global market for nitrous oxide delivery and mitigation systems is expanding, driven by increasingly stringent safety regulations regarding occupational exposure and environmental impact. However, a fragmented landscape exists with significant regional disparities across surgical and obstetric departments.

In surgical settings (Operating Rooms), N_2O usage remains substantial in specific regions like the Netherlands, where approximately 25% of hospitals (at least 18 out of 70) actively utilize the gas in 2023 [36]. Conversely, broader European penetration remains limited, with advanced N_2O infrastructure integrated into only 5% to 10% of hospitals [37].

The obstetric sector exhibits more pronounced regional variations:

- **The United Kingdom & Commonwealth (Australia, New Zealand, Canada):** Act as market leaders. Nitrous oxide (Entonox) is the clinical gold standard, available in virtually 100% of delivery rooms, with utilization rates among parturients ranging between 76% and 80% [24, 38].
- **The United States:** This market is currently in a "re-emergence" phase. Following FDA approval of modern delivery infrastructure around 2012, availability grew from less than 1% to over 25% of maternity hospitals, positioned as a low-intervention alternative to epidural analgesia [39, 40].
- **Continental Europe (Germany, France, Belgium):** Adoption remains significantly lower, as clinical preference leans heavily toward epidural anesthesia (60% to $>$ 80%) [41].

1.4.2 Analysis of Available N_2O Management Technologies

This section presents the empirical findings from a systematic analysis of the N_2O management and sedation systems dataset ($N = 60$ unique devices). The data are structured across six primary dimensions: market concentration, clinical distribution, technological archetypes, carbon mitigation efficacy, lifecycle waste streams, and economic expenditure profiles.

Market Landscape and Device Identification
The data infrastructure reveals a total of 60 devices distributed across 19 medical manufacturers. The market exhibits high polarization, concentrated around a few established clinical delivery and infrastructure suppliers. *Porter* represents the largest market share within the dataset with $n = 16$ systems (26.7%), followed by *Accutron* ($n = 7$, 11.7%) and *Puramed* ($n = 7$, 11.7%). High-end integrated anesthesia workstations are dominated by *Dräger* ($n = 6$, 10.0%). Conversely, dedicated climate mitigation architectures engineered specifically for active gas destruction or capture are constrained to a specialized cohort of innovative niche manufacturers: *Medclair AB* ($n = 3$), *MedicVent* ($n = 3$), and *Linde Healthcare* ($n = 3$).

Clinical Eligibility and Departmental Mapping
To evaluate the clinical versatility of the inventoried fleet ($N = 60$), each device was assessed for departmental compatibility based on its technical specifications (e.g., flow-rate mechanics and valve configurations). Because individual systems frequently satisfy the operational criteria for multiple medical specialties, these departmental designations are not mutually exclusive.

The analysis indicates a high compatibility profile for pediatric and outpatient procedural applications (Table 1). Out of the 60 total systems, the highest compatibility is found in Pediatrics, with $n = 47$ systems (78.3%) meeting the necessary criteria for sedation of short interventions. This is followed closely by Dentistry, where $n = 39$ systems (65.0%) are technically applicable. Emergency Medicine and Obstetrics exhibit the same amount of compatibility profiles ($n = 26$, 43.3% each). The Operating Room are compatible with $n = 24$ devices (40.0%), while Intensive Care and Recovery units represent the smallest amount of compatible systems ($n = 6$, 10.0%).

Clinical Department	Compatible Devices (n)	Compatibility Rate (%)[a]
Pediatrics	47	78.3%
Dentistry	39	65.0%
Emergency Medicine	26	43.3%
Obstetrics	26	43.3%
Operating Rooms	24	40.0%
Intensive Care / Recovery	6	10.0%

[a] Percentages are calculated relative to the total fleet ($N = 60$). Values do not sum to 100% as individual devices may be compatible with multiple departments.

Table 1: Departmental Compatibility and Technical Applicability of Sedation Systems ($N = 60$)

Technological Archetypes and Functional Mechanisms

To evaluate the technical baseline of the market, the systems were evaluated across five key operational capabilities: ventilation delivery, local extraction, monitoring, structural gas capture, and active chemical/catalytic conversion. Delivery mechanisms are present in $n = 34$ devices (56.7%), and localized scavenging configurations are featured in $n = 29$ units (48.3%). True carbon mitigation mechanisms remain uncommon; active destructive technologies are incorporated in only $n = 7$ units (11.7%), while specialized physical gas capture configurations are restricted to $n = 3$ units (5.0%). Real-time gas tracking and monitoring interfaces are present in $n = 6$ systems (10.0%).

Environmental Impact and the Carbon Mitigation Paradox

A cross-tabulation evaluating active destruction systems against N_2O emission reduction metrics unveils a distinct operational paradox between local occupational safety and global atmospheric protection (Table 2). Out of the 60 analyzed configurations, $n = 47$ (78.3%) provide zero active greenhouse gas destruction. Within this non-mitigating cohort, $n = 18$ units (30.0%) are explicitly designated as "displacement emissions" via scavenging systems. These setups successfully protect healthcare professionals from indoor exposure but vent 100% of the unmetabolized N_2O directly into the atmosphere.

True active carbon mitigation is verified in only $n = 7$ devices (11.7%), executing automated thermal or catalytic cracking. Additionally, $n = 6$ systems (10.0%) achieve a validated *indirect* environmental mitigation status; these are exclusively high-end closed-circuit anesthesia workstations (e.g., the *Dräger Zeus* and *Atlan* series) that lower total carbon output by utilizing low-flow gas recirculation parameters to minimize raw gas consumption.

N_2O Reduction Category	Active Destruction (*Yes*)	No Destruction (*No*)	Total
Active Mitigation (*Yes*)	7	0	7
Indirect Mitigation (*Indirect*)	0	6	6
No Mitigation / Local Displacement	0	47	47
Total	**7**	**53**	**60**

Table 2: Cross-Tabulation of N_2O Reduction Efficacy by Destruction Capabilities

Lifecycle, Maintenance, and Waste Stream Characteristics

Sustainability metrics diverge significantly regarding raw hardware longevity and ongoing hospital waste generation. A profound reliance on single-use plastics is evident, with $n = 28$ devices (46.7%) possessing mandatory plastic disposable configurations (primarily disposable multi-layer nasal hoods, bacterial filters, and patient-side breathing tubes), channelizing a consistent volume of solid medical or regular clinical waste.

From an asset-lifecycle perspective, $n = 15$ devices (25.0%) exhibit a functional lifespan exceeding 10 years (10+ years), and $n = 15$ (25.0%) operate within an 8–12 year lifespan. Centralized medical gas supply systems and heavy mechanical pipeline components display the highest longevity, spanning between 15 and 25 years ($n = 8$, 13.3%). Ongoing operations impose a substantial burden on hospital technical departments: mandatory annual or periodic preventative maintenance schedules are required for the vast majority of units ($n = 42$, 70.0%), and active systematic calibration routines are required for $n = 25$ systems (41.7%). Equipment fault sensitivity is predominantly classified as low ($n = 30$, 50.0%) or low-to-medium ($n = 19$, 31.7%).

1.4.3 Case Study of Systems used in LUMC

To evaluate the operational and environmental implications of N_2O management, this subsection provides a comparative analysis of two prominent architectural configurations deployed within the LUMC: the *Medclair AB Mobile Destruction Unit* and the *Puramed Central Anaesthetic Gas Scavenging System (AGSS)*. As detailed below and synthesized in Table 3, these systems represent distinct technical archetypes, contrasting decentralized climate mitigation against centralized occupational protection frameworks.

Medclair AB Mobile Destruction Unit Introduced in 2019, the *Medclair AB Mobile Destruction Unit* is a point-of-use, active carbon-mitigation technology designed to be deployed downstream of existing localized Anesthetic Gas Scavenging (AGS) setups (Figure 2).

- **Functional Mechanism:** The unit intercepts exhaled N_2O directly at the gas exhaust vector, utilizing a thermal/catalytic reactor bed to crack the compound into inert nitrogen (N_2) and oxygen (O_2). It achieves low-to-medium residual emissions depending on matching gas-flow velocities.
- **Clinical and Environmental Footprint:** Certified with a CE mark, it is clinically cross-functional across Operating Rooms, Obstetrics, Emergency Medicine, Pediatrics, and Dentistry. Crucially, the system utilizes no single-use plastic components, generating zero solid medical disposable waste.
- **Operational Trade-offs:** The catalytic process demands significant electrical power, yielding local heat development and audible ambient noise. These factors necessitate specific clinical installation criteria, including adequate room ventilation and physical space buffers.
- **Lifecycle and Cost Structure:** The unit displays high hardware durability, with an estimated asset lifespan exceeding 15 years and long-term maintenance cycles (10+ years). Its financial profile exhibits a medium Capital Expenditure (CAPEX), while the Operational Expenditure (OPEX) is primarily dictated by utility costs and periodic catalytic servicing intervals.

Figure 2: Medclair AB Mobile Destruction Unit in clinical setting [42]

Puramed Central Anaesthetic Gas Scavenging System (AGSS) The *Puramed Central AGSS* represents a foundational, infrastructure-scale clinical safety mechanism engineered to comply with strict statutory workplace exposure limits (Figure 3).

- **Functional Mechanism:** Operating as an active centralized infrastructure layout, it leverages a heavy mechanical medical vacuum to rapidly evacuate waste gases away from the patient's breathing zone and the clinician's immediate workspace, routing them outside the building envelope.
- **The Environmental Paradox:** While achieving high operational reliability and clinical safety markers, the system provides zero active carbon mitigation. Its technical principle relies entirely on displacement, resulting in high residual emissions as 100% of the harvested N_2O is directly vented unmodified into the atmosphere.
- **Lifecycle and Cost Structure:** Engineered for institutional longevity, the core mechanical components display an operational lifespan of 15 to 25 years under a regimen of periodic preventative maintenance. However, the system requires recurring consumable parts, such as patient-side hoses, clinical interfaces, and adapters—partially composed of single-use plastics, creating an ongoing solid waste stream.

Figure 3: Puramed Central Anaesthetic Gas Scavenging System (AGSS) [43]

Technical Metric	**Medclair Mobile Destruction Unit**	**Puramed Central AGSS**
System Archetype	Decentralized End-of-Pipe Cracking	Central Safety Infrastructure
Primary Objective	Climate/Carbon Footprint Reduction	Occupational Exposure Safety
Active N_2O Reduction	Yes (Catalytic Cracking)	No (Atmospheric Displacement)
Residual Gas Emission	Low to Medium	High (100% of evacuated gas)
Solid Waste Stream	None	Technical / Single-use Plastic
Asset Lifespan	15+ Years	15–25 Years
Primary Expense Drivers	Electricity / Catalyst Servicing	Consumables / Routine Vacuum Service

Table 3: Technical Comparison: Medclair Mobile Destruction vs. Puramed Central AGSS

1.4.4 Case Study of Centralized Destruction Systems

To evaluate the scaling efficiencies of centralized "end-of-pipe" carbon reduction strategies, this subsection provides a targeted comparative analysis of two prominent architectural configurations within the dataset: the *Medclair AB Central Destruction Unit (CDU)* and the *MedicVent Nitrous Oxide Destructor DeN2O-S3*. These systems represent highly specialized infrastructure designed to process collected anesthetic gas downstream of hospital-wide Anesthetic Gas Scavenging (AGS) networks. A side-by-side synthesis of their primary technological metrics, lifecycles, and operational trade-offs is detailed below and consolidated in Table 4.

Medclair AB Central Destruction Unit (CDU) The *Medclair AB Central Destruction Unit (CDU)* is an active, facility-scale greenhouse gas mitigation system engineered for hospital-wide integration (Figure 4).

- **Functional Mechanism:** Operating exclusively as a centralized supporting infrastructure component, the CDU manages extracted gas streams across a universal clinical scope. The underlying mechanism utilizes active catalytic destruction to split the N_2O molecule into inert nitrogen (N_2) and oxygen (O_2), achieving low-to-medium residual emissions depending on specific operational flow loads.
- **Clinical and Environmental Footprint:** Certified with a CE mark, it handles gas streams at an institutional throughput capacity across Operating Rooms, Obstetrics, Emergency Medicine, Pediatrics, and Dentistry. Crucially, the system is free from single-use plastics and its reactive filtration beds do not produce hazardous or chemical waste streams during replenishment, resulting in a cleaner post-lifecycle footprint.
- **Operational Trade-offs:** The active catalytic process relies entirely on large-scale electrical power, yielding operational trade-offs such as significant local heat generation. These factors dictate strict facility installation criteria, including integration into dedicated technical rooms with robust forced ventilation.

- **Lifecycle and Cost Structure:** The unit features an estimated hardware lifespan of 10 to 15 years, utilizing generic periodic maintenance windows alongside automated alarms and leak detection mechanisms. The economic cost profile is heavily driven by initial facility-scale capital requirements (CAPEX) for technical room preparation, while ongoing operational expenditure (OPEX) is determined by utility electricity demands.

Figure 4: Medclair AB Central Destruction Unit (CDU) infrastructure [44]

MedicVent Nitrous Oxide Destructor DeN2O-S3 The *MedicVent Nitrous Oxide Destructor DeN2O-S3* represents an alternative engineering approach to active gas decomposition, serving as a direct competitor within the central climate-mitigation sector (Figure 5).

- **Functional Mechanism:** Similar to the Medclair CDU, the DeN2O-S3 operates purely as a downstream, supportive destruction system that intercepts evacuated scavenging flows. It executes automated internal N_2O cracking to break down the compound, achieving a comparable low-to-medium residual emission rating.
- **The Environmental Paradox:** While achieving a significant reduction in gaseous carbon footprint, the system's reliance on recurring materials introduces an ongoing environmental trade-off. The platform systematically depends on replaceable catalyst cartridges or media modules over short-term intervals, which converts the ongoing operational waste stream into industrial or hazardous chemical waste requiring specialized disposal protocols.
- **Lifecycle and Cost Structure:** Built for extended structural durability, the hardware boasts a maximum lifespan spanning 10 to 20 years. However, it enforces a rigid preventative maintenance and cartridge replacement schedule every 6 to 12 months, yielding medium fault sensitivity. Consequently, the long-term cost profile is heavily influenced by recurring procurement fees and hazardous waste disposal liabilities rather than pure electrical utility outlays.

Technical Metric	**Medclair AB Central CDU**	**MedicVent DeN2O-S3**
System Archetype	Central Destruction Unit	Nitrous Oxide Destructor
Primary Objective	Hospital-wide / Multi-room	Scavenging-stream Dedicated
Active N_2O Reduction	Yes (Catalytic Destruction)	Yes (Catalytic Decomposition)
Residual Gas Emission	Low to Medium	Low to Medium
Solid Waste Stream	None	Industrial / Chemical Waste
Asset Lifespan	10–15 Years	10–20 Years
Primary Expense Drivers	Spatial Engineering / Electricity	Media Replacement / Hazardous Disposal

Table 4: Technical Comparison: Medclair AB Central CDU vs. MedicVent DeN2O-S3

Figure 5: MedicVent Nitrous Oxide Destructor DeN2O-S3 facility system [45]

1.5 Discussion

The empirical findings of this study highlight a complex intersection of regulatory frameworks, architectural constraints, and resource distribution that shapes the global landscape of N_2O management. The selection of an optimal technological infrastructure is heavily contingent upon specific departmental characteristics, the nature of clinical interventions, and the overall volume of patient care.

At the institutional level, distinct departmental trends govern the utilization of nitrous oxide. Within Operating Rooms, a structural decline in N_2O consumption is observed, driven by a clinical shift toward Total Intravenous Anesthesia (TIVA). This transition is heavily supported by a growing body of literature demonstrating that intravenous agents achieve equivalent anesthetic efficacy while eliminating the environmental and occupational liabilities associated with inhalation gases [46]. Conversely, Obstetrics departments are experiencing a resurgence in demand for N_2O administration. This shift is largely driven by patient preferences for less invasive, non-pharmacological labor experiences. Compared to epidural analgesia which restricts maternal mobility, prolongs labor stages, and routinely necessitates secondary interventions such as bladder catheterization N_2O is increasingly favored as a mobile, patient-controlled alternative that preserves physiological autonomy during childbirth [47].

1.5.1 Regulatory Divergence and the Normalization of Clinical Delivery

A primary driver of the regional disparities observed in the results is the variation in national regulatory frameworks and clinical traditions. In jurisdictions such as the United Kingdom, the utilization of N_2O (predominantly as a 50:50 medicinal gas mixture) is highly normalized and supported by extensive centralized piped infrastructure [48]. This systemic integration is heavily reinforced by permissive regulatory standards; unlike in continental Europe, frontline clinical staff in the UK often do not require specialized postgraduate certification or intensive training to administer the gas during labor or minor procedures [49, 50].

Conversely, the regulatory landscape in the Netherlands and surrounding European nations is governed by strict occupational health and safety legislation focused on minimizing ambient exposure [51, 52]. These stringent protocols necessitate formal training pathways for clinical personnel and mandate advanced localized scavenging systems. Consequently, the administrative and educational burden shifts clinical preferences toward alternative analgesic modalities, such as epidural anaesthesia, resulting in the fragmented adoption rates identified in the market analysis.

1.5.2 Material Intensity and Geopolitical Stratification

The delivery of N_2O, even under minimal clinical safety thresholds, inherently demands a resource-intensive hardware ecosystem. A functioning patient circuit requires a continuous supply chain of specialized mouth-mask interfaces, directional demand valves, multi-layered delivery lines, and structural connectors [53]. When optimizing these setups to comply with modern occupational safety standards (e.g., integrating active scavenging and catalytic cracking architectures), the hardware footprint and logistical complexity increase exponentially.

This high baseline of material dependency inherently drives geopolitical stratification. Because the procurement of multi-layered patient delivery circuits, continuous single-use consumables, and technical maintenance services requires

robust capital allocations, the clinical utilization of N_2O remains overwhelmingly concentrated within well-funded healthcare systems of the Global North. This concentration, validated by the manufacturer distribution data, highlights a socioeconomic barrier to technology transfer; low- and middle-income countries (LMICs) face structural exclusion from implementing these sedation frameworks due to the prohibitive lifecycle costs of the required containment and mitigation infrastructure [54, 55].

1.5.3 Infrastructural Frameworks: Decentralized Cylinders versus Centralized Piping

The logistical mechanism selected for distributing medical N_2O within a healthcare facility functions as a primary structural determinant of the institution's total fugitive greenhouse gas burden. Two principal configurations are in widespread use: centralized piped manifold networks, in which compressed gas is routed from a bulk supply source through copper distribution lines to terminal wall outlets across the facility, and decentralized systems, in which portable cylinders are deployed directly at the point of care and connected to individual demand-valve delivery units.

Environmental performance of piped versus cylinder based distribution
Centralized manifold piping systems are inherently prone to chronic, distributed N_2O leakage at copper sub-structural joints, flexible hose connections on ceiling pendant arms, and terminal wall valves [56]. Because N_2O is a small, low-polarity molecule, it permeates the plastic hoses commonly used in ceiling-mounted boom arms across the full hose length under continuous pipeline pressure, resulting in losses that are independent of active clinical use [57]. Multi-site empirical audits conducted in Australia, Scotland, and the United States consistently document that 70% to 100% of institutionally procured N_2O is lost through pipeline infrastructure before reaching the patient [58, 59, 60]. Conversion to point-of-care cylinders directly coupled to individual anaesthesia workstations eliminates building-scale distribution losses by removing the pressurized distribution network entirely, and has been demonstrated to reduce non-clinical N_2O wastage by over 99% relative to centralized piped supply [57, 61].

The Dutch regulatory and professional landscape
Within the Netherlands, the displacement of centralized piped manifold infrastructure in favour of decentralized cylinder-based delivery is not mandated by a single law or guideline. But emerges instead from the convergent operation of occupational health law, national sustainability policy, and binding professional clinical standards.

The Dutch *Arbeidsomstandighedenwet* mandates reducing hazardous worker exposure to the lowest reasonably achievable level [62]. Absent a statutory public limit for N_2O, the operative enforcement benchmark is a private limit established by the *Arbocatalogus Inhalatieanesthetica* [63]. It mandates a time-weighted average (TGG-8u) of 152 mg/m^3 and an ALARA-based, monitoring-exempt target of 38 mg/m^3 [63, 64]. However, updated toxicological evidence led to stricter limits taking effect on 1 January 2026 [65]. Meeting these lower thresholds is largely incompatible with retaining centralized piped networks, which cause continuous background contamination that evades local scavenging [63].

The national *Green Deal Duurzame Zorg 3.0* (GDDZ 3.0), a 2023–2026 covenant between the Dutch government and over 550 healthcare organizations, mandates a 55% reduction in direct emissions by 2030 and full climate neutrality by 2050, explicitly targeting medicinal gases [66]. Because N_2O has a 100-year GWP of 273 -equivalents [9] and distribution losses constitute direct Scope 1 emissions, the systemic leakage inherent to centralized manifold systems is structurally incompatible with GDDZ 3.0 reporting compliance.

At the clinical governance level, the *NVA Leidraad Perioperatieve Zorg* (2024) mandates local protocols designating Total Intravenous Anaesthesia (TIVA) as the primary modality and minimizing N_2O use [67]. This professional standard is operationalized by the *Milieu Platform Zorg* (MPZ) as an auditable environmental criterion required for institutional certification [68]. Maintaining an operational, building-wide piped manifold system requires a permanent institutional commitment to N_2O distribution regardless of clinical consumption, making it structurally inconsistent with the intent of these directives.

International contrast
The Dutch trajectory stands in marked contrast to regulatory environments in which centralized piped N_2O delivery remains fully standardized. In England, NHS Health Technical Memorandum HTM 02-01 provides detailed design, installation, and operational management requirements for medical gas pipeline systems inclusive of N_2O, and continues to govern the maintenance of such infrastructure across NHS trusts [69, 70]. While NHS England has published supplementary guidance on minimizing occupational exposure to N_2O in healthcare settings, this guidance operates within the framework of continued piped infrastructure use rather than advocating for its decommissioning [71]. At the international level, NEN-EN-ISO 7396-1:2016, the harmonized standard for medical gas pipeline systems adopted in the Netherlands and across the European Union, continues to specify technical requirements for the design, installation, and commissioning of N_2O piped manifold systems, with national or regional departure from this baseline being at the discretion of individual jurisdictions [72]. This divergence illustrates that while the Dutch regulatory framework has, through the convergence of occupational health, sustainability, and clinical professional norms, structurally decoupled hospital carbon accounting from upstream network leakage losses, numerous other jurisdictions continue to permit and maintain centralized distribution infrastructure, thereby tolerating a continuous, unmitigated baseline of fugitive N_2O emissions independent of active patient therapy.

1.5.4 Typological Diversity and Market Architecture

The structural composition of the dataset reveals that while various systems are cross-functional across multiple departments, no single technological solution is globally applicable across all clinical contexts. A notable architectural dichotomy exists between manufacturers specializing in decentralized, mobile equipment and those engineering centralized infrastructure. Firms focusing on smaller, mobile devices exhibit a higher baseline of typological diversity, introducing a broader range of distinct product models to the market. This structural variance is enabled by the localized nature of mobile equipment, which allows for granular, modular configurations tailored to specific clinical applications.

Conversely, manufacturers of centralized, infrastructure-scale equipment maintain highly consolidated, low-variance product portfolios. These centralized platforms feature fewer distinct models but maintain wide operational versatility, rendering them highly adaptable across diverse clinical environments. Crucially, the volume of unique product models per manufacturer in the dataset does not correlate with actual market penetration or sales volumes. The registry counts purely reflect product line diversity rather than institutional installation frequency, representing a baseline data limitation regarding commercial market-share modeling.

1.5.5 Comparative Evaluation of Inhalation Subsystems

When evaluating the technical execution of N_2O delivery, infrastructure planners must choose between continuous-flow and demand-flow (flow-dependent) configurations. Demand-flow architectures represent a significantly more sustainable operational paradigm; by delivering the gas mixture exclusively during the patient's inspiratory phase rather than maintaining a constant flow, these systems drastically minimize raw gas consumption and waste. Consequently, the implementation of demand-flow systems offers strong financial incentives for healthcare facilities. The initial capital investment required to procure demand-flow hardware is directly offset by reduced procurement expenditures for raw medicinal gas, creating a clear, short-term return on investment (ROI).

For scavenging and gas extraction architectures, the market offers highly diverse options from numerous vendors, which can be categorized into decentralized mobile units and centralized installations. Centralized gas scavenging configurations function as highly efficient, institutional safety mechanisms; operating from a centralized technical facility, they maintain a continuous negative pressure across procedural rooms, providing a true "plug-and-play" interface where clinicians simply connect a passive exhaust hose to a wall terminal.

However, centralized scavenging installations demand substantial upfront Capital Expenditure (CAPEX) due to the structural renovations and specialized pipeline networks required within the building envelope. From a purely environmental standpoint, mobile and centralized scavenging systems exhibit identical global warming footprints. Both mechanisms rely entirely on atmospheric displacement, venting 100% of the collected, unmodified N_2O directly into the outside air. Thus, neither system provides an inherent sustainability advantage over the other without downstream mitigation.

Alternative physical carbon-capture paradigms, such as adsorption-based storage systems, currently face significant implementation barriers. While capable of trapping waste gases at the point of use, the market currently lacks commercial downstream processing networks capable of purifying and recycling the captured gas back into the medical supply chain. In the absence of an integrated circular recycling loop, healthcare facilities logically favor standard scavenging setups or active destruction architectures.

Active cracking (destruction) systems represent the most technologically sustainable option currently available on the market, as they actively mitigate the greenhouse impact of N_2O by thermally or catalytically reducing it to inert N_2 and O_2. These are similarly bifurcated into mobile and centralized archetypes:

- **Mobile Destruction Units:** Highly effective for scheduled or elective care pathways (e.g., outpatient pediatric interventions or planned dentistry). However, their integration into acute workflows is constrained by a mandatory 30-minute thermal pre-heating phase required to reach catalyst activation temperatures, rendering them ill-suited for immediate, unplanned interventions.

- **Centralized Destruction Units:** Avoid clinical workflow delays by operating continuously. However, this configuration imposes elevated long-term operational expenditures (OPEX) and high energy baseline footprints, as the catalytic reactor cores must be maintained at operating temperatures continuously to ensure immediate readiness across the hospital network.

Gas monitoring systems in this domain serve primarily as patient safety mechanisms rather than environmental mitigation tools. The monitoring hardware in the current dataset is engineered to track the precise concentration ratios of N_2O relative to O_2 within the breathing circuit to prevent hypoxic mixtures. Because these devices are not designed to monitor clinical sedation depth (e.g., via Bispectral Index monitoring or standardized clinical sedation scales) [73], they cannot dynamically optimize or restrict gas administration volumes to minimize clinical waste.

1.5.6 Hygiene Standards and Residual Lifecycles

When managing technical lifecycles and maintenance protocols, a fixed baseline of physical waste generation remains unavoidable. Due to strict clinical hygiene guidelines and infection-control mandates, elements such as bacterial filters,

specialized sealing gaskets, and patient-side interfaces cannot be reprocessed or laundered. Consequently, institutional patient safety and cross-contamination prevention must take absolute precedence over material sustainability goals, reinforcing a continuous, non-reducible stream of single-use medical waste within the lifecycle model.

1.5.7 Economic Drivers and Financial Data Vulnerabilities

The pronounced transparency gap identified within the financial reporting layers of the dataset introduces a notable analytical limitation that warrants careful interpretation. The absence of quantitative Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) metrics across 98.3% of the evaluated public and manufacturer-supplied entries ($n = 59$ missing data points) effectively precludes the execution of rigorous statistical correlation modeling or formalized cost-effectiveness analyses. This systematic omission of fiscal data likely stems from the proprietary commercial interests of medical equipment manufacturers and a historical lack of standardized economic reporting in hospital sustainability audits. Consequently, this data deficit forces healthcare decision-makers to rely on qualitative structural criteria rather than precise economic projections when evaluating the long-term viability of clinical carbon-mitigation strategies.

Despite these quantitative data limitations, the qualitative systemic criteria compiled in this study reveal a distinct fiscal bifurcation that carries major strategic implications for institutional asset allocation. The economic profile of medical gas infrastructure can be divided into two competing paradigms:

1. **Clinical Delivery and Local Scavenging Components:** This pathway is characterized by relatively low-barrier initial procurement fees, which may deceptively position decentralized systems as financially attractive. However, this entry-level affordability is offset by high, compounding recurring operational costs (OPEX). These long-term outlays are driven by continuous single-use consumable plastic configurations and the necessity for rigid technician calibration intervals to ensure statutory safety compliance.

2. **Centralized Destructor and Recycling Units:** Conversely, facility-scale mitigation networks demand intensive upfront capital investments (CAPEX). These expenses are driven by the structural demands of physical facility modifications, such as the allocation of dedicated technical rooms and the engineering of specialized, insulated ventilation pathways. Once established, however, the stabilization of its OPEX profile depends less on clinical volume and more on steady hourly electrical power consumption and the recurring costs of industrial or hazardous waste disposal protocols for saturated catalytic beds or exhausted reaction cartridges.

This fiscal divide demonstrates that a successful transition to low-carbon anesthesia cannot be evaluated solely through the lens of carbon efficiency. Hospital administrations must weigh immediate facility-scale infrastructure investments against the long-term, invisible operational drain of clinical consumables, balancing upfront capital constraints against recurring departmental budgets.

1.5.8 Institutional Implementation and Workflow Dynamics: The LUMC Paradigm

At the LUMC, the operational integration of these technologies is demonstrated by the concurrent deployment of the *Medclair AB Mobile Destruction Unit* and the *Puramed Centraal AGSS*. The Medclair Mobile Unit is integrated within the pediatric hospital division, where it supports elective care and brief, scheduled procedural interventions. Conversely, the Puramed Central AGSS services highly unpredictable, unplanned clinical pathways within the Obstetrics division, alongside a structurally comparable centralized vacuum network deployed in the Emergency Department.

This institutional deployment highlights a clear trade-off between installation complexity and clinical workflow efficiency. The Medclair Mobile Unit offers rapid, friction-free implementation, bypassing the need for structural capital works or technical modifications to the facility's walls. However, within active clinical workflows, medical staff consistently report that the centralized Puramed AGSS provides a superior, faster user experience. The central infrastructure eliminates hardware pre-heating delays and equipment transport logistics, delivering an instantaneous, plug-and-play interface essential for acute or time-critical emergency interventions.

Consequently, when a healthcare facility evaluates the deployment of a centralized destruction node, several infrastructural prerequisites must be considered. Centralized destructors cannot operate in isolation; they must be coupled directly to an underlying centralized scavenging network capable of safely extracting gas from the point of care. If a facility lacks an established AGSS infrastructure, the deployment of a central destructor necessitates a major capital renovation to install the required internal pipeline networks.

Furthermore, strong vendor ecosystem synergies exist within this market sector. For instance, MedicVent maintains close technical and commercial alignment with Puramed infrastructure systems; therefore, institutions possessing an established footprint from either vendor can leverage these existing relationships to streamline engineering compatibility and procurement pipelines. Finally, procurement models must account for the continuous energy baseline requirements inherent to central destruction architectures to create the same plug-and-play effect, which introduce long-term structural increases to institutional utility expenditures.

1.5.9 Strategic Procurement Frameworks: Pre-Implementation Auditing and R-Ladder Alignment

The deployment or technical replacement of N_2O clinical infrastructure must not occur in an architectural vacuum; rather, it dictates a rigorous, department-specific needs assessment prior to any capital procurement. The physical implementation of delivery, scavenging, or cracking hardware must be precisely tailored to the specific operational workflows of localized healthcare professionals and the exact nature of the clinical interventions performed within that sector.

In highly regulated healthcare environments such as the Netherlands, the integration of advanced scavenging networks or active catalytic cracking units is a statutory mandate rather than an optional sustainability choice. These technical interventions are legally required to maintain ambient gas levels strictly below the statutory time-weighted average exposure limits enforced by national labor laws. A matching principle applies to the deployment of decentralized gas cylinders over centralized infrastructure pipelines, as the inherent containment security of cylinders is technically required to prevent the diffuse, structural micro-leaks that violate occupational safety ceilings set to protect healthcare personnel from unwanted reproductive and neurological risks [74].

Crucially, this strict legal and structural architecture drives a profound institutional awareness regarding the chemical hazards, occupational risks, and environmental liabilities of nitrous oxide. By raising the technical and administrative thresholds for its deployment, these stringent frameworks naturally suppress the baseline clinical inclination to utilize the gas mixture. Consequently, this systemic discouragement acts as an upstream behavioral intervention, aligning the institution's clinical culture directly with the highest tier "Refuse" of the circular economy R-ladder framework before end-of-pipe technology is ever deployed.

Therefore, when an individual department evaluates the initial introduction of nitrous oxide workflows, or when an established division prepares to replace its legacy gas systems, a comprehensive lifecycle emission and fiscal audit must be executed. It is critically imperative to mathematically model the precise variance between standard scavenging systems and active catalytic cracking architectures. Because traditional scavenging configurations merely displace 100% of the greenhouse gas into the outside atmosphere while cracking systems actively degrade the molecules into inert elements, a multi-variable calculation must be performed to balance the theoretical degradation potential against patient compliance and facial mask seal ergonomics in acute care environments [75].

This analytical modeling must integrate both quantitative carbon mitigation capacities and multi-tiered financial profiles (CAPEX vs. OPEX), matching recent academic directives for thorough techno-economic and cost-benefit assessments to establish effective healthcare emission control strategies [76]. Only through this dual-parameter evaluation can hospital administrations make strategic infrastructure choices that align long-term capital investments with genuine environmental performance targets.

2 Current Practice & Case Study (LUMC)

2.1 Introduction

While the technical landscape of N_2O management systems is defined, the practical implementation within complex clinical environments remains heterogeneous. This section investigates the specific infrastructure and regulatory compliance of a representative Dutch academic hospital: the LUMC. To establish a standardized metric for environmental impact, the Carbon Dioxide Equivalent (CO_2-eq) is utilized as a common denominator for all anesthetic gas emissions. However, a comprehensive evaluation must also account for secondary factors, including single-use plastic waste and clinical workflow efficiency. Consequently, this case study was designed to characterize the current utilization of N_2O and identify the drivers of clinical evolution through the following research questions:

Main Question: What is the current landscape of N_2O utilization at LUMC, and how has the clinical application evolved in recent years?

1. What are the quantitative consumption volumes and qualitative utilization patterns (stratified by department and administration method) at LUMC?
2. How has the volume and indication for N_2O use changed over the last 7 years, and what factors drove these shifts?
3. What specific hardware and infrastructure are currently in place at LUMC for delivery and waste gas management?
4. Which clinical administration procedures are used for N_2O interventions, and how do they differ per department?

2.2 Theoretical Framework

Nitrous oxide is established in clinical literature as a versatile anxiolytic and analgesic agent, utilized across diverse medical disciplines and age groups for brief, mild-to-moderate painful procedures. Its primary clinical utility is derived from its unique pharmacokinetic profile, characterized by a rapid onset, ease of titration, short duration of action, and swift psychomotor recovery.

2.2.1 Clinical Efficacy and Procedural Utility

The literature indicates that the efficacy of N_2O is highly context-dependent. While it possesses intrinsic analgesic properties, its added value appears limited in settings where effective local anesthesia is already established [77, 78]. Furthermore, for highly invasive procedures, N_2O often proves insufficient as a standalone analgesic, frequently requiring conversion to deeper sedation or acting merely as an adjunct to more potent interventions [79, 80].

In pediatric care, N_2O is particularly valued for reducing procedural distress and potential psychological trauma during brief interventions [93, 95]. Evidence suggests that in minor pediatric procedures, such as venous cannulation, N_2O provides analgesic effectiveness comparable to topical anesthetic creams (e.g., EMLA), while offering superior recovery profiles compared to systemic sedatives like intranasal dexmedetomidine [81, 82, 83].

2.2.2 Comparative Effectiveness vs. Active Alternatives

A critical component of the current theoretical landscape is the evaluation of N_2O against active pharmacological and non-pharmacological alternatives. Table 5 synthesizes how N_2O compares across various clinical settings.

Clinical Setting	**Comparator(s)**	**Key Evidence & Findings**
Gastroenterology	Propofol / Midazolam	Similar pain relief and satisfaction;N_2O facilitates significantly faster psychomotor recovery [84, 85].
Obstetrics	Neuraxial Analgesia	N_2O is often inferior; high conversion rates to epidural analgesia are frequently observed [86, 87].
Oral/Dental Surgery	Local Anesthesia / IV Sedation	N_2O is effective for anxiety, but local anesthetic blocks remain the cornerstone for primary pain control [88, 89, 90].
Emergency Care	Systemic Opioids	N_2O provides rapid short-term relief, often comparable to or synergistic with opioids for acute pain [91, 92].

Table 5: Comparative Analysis of N_2O and Alternative Modalities

2.2.3 Sustainability and Environmental Impact

A salient theme in contemporary anesthesia research is the environmental burden of inhalational agents. N_2O is a potent greenhouse gas with a high GWP [93]. To put this into clinical perspective, a typical obstetric delivery utilizing unmitigated nitrous oxide analgesia involves the consumption of approximately 500 to 1,000 liters of a 50:50 N_2O/O_2 mixture (e.g., Entonox/Relivopan). This volume of gas is estimated to generate a mean carbon footprint of approximately 139 kg CO_2-eq [94], an emission equivalent to driving an average passenger vehicle for roughly 550 kilometers [95].

The reviewed evidence suggests that the routine use of N_2O is increasingly difficult to justify when lower-impact alternatives, such as intravenous (IV) sedatives, regional techniques, or emerging non-pharmacological strategies like Virtual Reality (VR), yield comparable clinical outcomes [96, 97, 98].

However, a comprehensive lifecycle assessment requires evaluating the environmental trade-offs of these alternatives. Intravenous agents (e.g., propofol, remifentanil) present a drastically lower climate impact than inhalational gases, as their lifecycle carbon footprint is limited to production, sterilization, and logistics rather than direct atmospheric emissions [95]. Nonetheless, IV anesthesia introduces other ecological burdens, notably significant biomedical plastic waste from syringes and IV lines [99], alongside the ecotoxicological risk of propofol residues entering aquatic ecosystems through hospital wastewater due to poor biodegradability [100]. Non-pharmacological modalities like VR avoid chemical and medical waste entirely, though they incur minor upstream carbon costs during hardware manufacturing and localized electricity consumption during operation. Consequently, while alternatives are not entirely devoid of environmental impact, transitioning toward "green anesthesia" via these modalities represents a profound net reduction in total global warming potential when clinically appropriate.

2.2.4 Monitoring and Physiological Considerations

The theoretical framework must also account for the influence of N_2O on anesthetic monitoring. Research indicates that N_2O can alter EEG-derived indices, such as the Bispectral Index (BIS), potentially complicating the assessment of anesthetic depth independently of the patient's actual sedation level [101, 102]. Additionally, its association with increased postoperative nausea and vomiting (PONV) in specific contexts, such as gynecologic laparoscopy, further nuances its clinical profile [103, 96].

2.2.5 Law and legal restrictions for the use of Nitrous Oxide

The utilization of N_2O in a clinical setting is governed by a complex framework of Dutch and European legislation.

- The Medicines Act (*Geneesmiddelenwet*) Medical-grade N_2O is classified as a medicinal product. Consequently, it requires marketing authorization from the *College ter Beoordeling van Geneesmiddelen* (CBG). It is a prescription-only substance, and the hospital pharmacist is legally responsible for its procurement and quality assurance.
- The Opium Act (*Opiumwet*) As of January 1, 2023, N_2O was designated as a List II substance. While medicinal use is explicitly exempted from the prohibition, hospitals are required to implement robust diversion control measures to prevent recreational misuse.
- The Working Conditions Act (*Arbeidsomstandighedenwet*) To protect personnel from chronic exposure, the Dutch government maintains a Maximum Acceptable Concentration (MAC). For N_2O, this is defined as 152 mg/m^3 (8-hour time-weighted average). Compliance necessitates the use of active scavenging systems and high-efficiency ventilation.
- Storage and Transport (PGS 15 & ADR) As a pressurized dangerous good, storage must comply with PGS 15 (fire safety and ventilation standards), while international and domestic transport must adhere to ADR regulations.

2.3 Methods

2.3.1 Study Design and Setting

This study was designed as a retrospective, descriptive institutional case study investigating the procurement, clinical utilization patterns, and environmental footprint of medical N_2O at the LUMC. LUMC is an 882-bed tertiary academic teaching hospital located in the Netherlands. The period under empirical investigation spanned seven consecutive years, from January 1, 2019, through December 31, 2025, capturing institutional shifts prior to, during, and following the COVID-19 pandemic, as well as the introduction of new surgical interventions.

2.3.2 Data Collection: Quantitative Consumption

Quantitative logistics and inventory data were obtained in cooperation with the central institutional purchasing and procurement division. To ensure data validity and capture potential structural discrepancies, consumption volumes were cross-referenced using two independent datasets extracted from institutional enterprise resource planning (ERP) systems:

- **Procurement Portal Orders:** Digital logbooks documenting all direct, web-based electronic purchase orders submitted to external gas distributors for cylinder replenishment. This dataset is compiled and maintained internally by procurement personnel at the LUMC purchasing department. Notably, these macro-level data are aggregated exclusively at the institutional scale, preventing the direct isolation of department-specific procurement volumes.
- **Track-and-Trace Inventory System Logs:** Barcode scanning records logging the physical delivery, destination department, and internal tracking status of individual gas cylinders within the facility. Management and verification of this tracking system are the administrative responsibility of an embedded representative from the gas manufacturer (Linde Gas). In contrast to the procurement data, these granular tracking logs are available at a highly localized, department-specific resolution.

Discrepancies may arise between these datasets because the calendar year of procurement does not necessarily coincide with the calendar year of clinical consumption.

Data metrics were standardly recorded as the absolute number of physical cylinders ordered and delivered per calendar year, stratified by commercial product formulation: Relivopan (a compressed 50/50% gaseous N_2O/O_2 mixture) and Niontix (100% pure liquefied N_2O). Both gas formulations are supplied in standard cylinders featuring a 10-liter geometric water capacity.

2.3.3 Data Collection: Qualitative Infrastructure and Protocols

To contextualize the quantitative consumption trends and map operational workflows, a mixed-methods qualitative assessment was executed across the four consumer departments (Emergency Department, Children's Hospital, Obstetrics and Gynecology, and Surgery). This phase consisted of two core components:

- **Semi-Structured Stakeholder Interviews:** Targeted qualitative interviews were conducted with key clinical and operational personnel, including department nursing coordinators, medical managers, and technical specialists. These queries documented local workflow demands, historical choices regarding safety systems, protocol origins, and operational satisfaction with gas-delivery hardware.
- **Physical Site Inspections:** Direct on-site evaluations of the hospital's mechanical infrastructure were carried out to trace gas pathways. This included inspecting cylinder manifolds, local transport carts, mobile catalytic decomposition hardware, and centralized vacuum-scavenging exhaust assemblies. Infrastructure configurations were audited against Dutch occupational health and environmental safety guidelines, specifically the Working Conditions Act (*Arbowet*) and the Hazardous Substances Publication Series (*PGS 15*).

2.3.4 Environmental Impact Modeling (CO_2-eq Calculations)

The global warming impact of unmitigated gas consumption was modeled by converting raw cylinder procurement volumes into equivalent masses of carbon dioxide (CO_2-eq). In accordance with the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6), a 100-year GWP_{100} value of 273 was applied for pure nitrous oxide. Environmental calculations relied on standard physical constants, assuming a gas density for N_2O of 0.00183 kg/L at standard temperature and pressure (0°C and 1.013 bar).

Mathematical modeling differed by product physical state as follows:

1. General Base Equation
The core environmental conversion for an absolute mass of released nitrous oxide gas is expressed as:

$$\text{Mass of } N_2O \text{ (kg)} \times GWP_{100} = \text{Mass of } CO_2\text{-eq (kg)}$$

2. Calculation for Relivopan (10L Cylinder Gaseous Mixture)
Relivopan is supplied as a highly compressed gas mixture under an operational filling pressure of 170 bar. The absolute mass of active N_2O contained within a single 10-liter water-capacity cylinder was calculated using the ideal gas law approximation under standard ambient conditions:

$$\text{Total Expanded Gas Volume} = 10 \text{ L (Water Capacity)} \times 170 \text{ bar} = 1,700 \text{ L} \quad (1)$$

Given the 50/50% volumetric blend, the fractional volume allocated exclusively to nitrous oxide equals 50% (850 L). Applying the standard density constant yields the net mass per cylinder:

$$\text{Net Mass of } N_2O = (1,700 \text{ L} \times 0.50) \times 0.00183 \text{ kg/L} = 1.5555 \text{ kg} \quad (2)$$

Multiplying by the global warming potential (GWP) determines the carbon equivalent baseline value per cylinder:

$$1.5555 \text{ kg} \times 273 = 424.66 \text{ kg } CO_2\text{-eq} \tag{3}$$

(Note: For institutional consistency with raw procurement logs and legacy tracking frameworks, an operational multiplier of 421.40 *kg CO_2-eq per cylinder was utilized during spatial mapping to account for technical fill variances.)*

This institutional fill variance is primarily attributed to thermodynamic fluctuations, such as ambient temperature deviations during the filling process, and manufacturer tolerances, both of which introduce minor variability into the actual gas density and internal cylinder volume.

3. Calculation for Niontix (10L Cylinder Liquefied Gas)
Unlike compressed mixtures, Niontix is stored inside the cylinder under pressure as a liquefied gas, meaning volume-by-pressure equations are inapplicable. A standard commercial 10-liter Niontix cylinder is filled with a certified, pre-weighed mass of exactly 7.5 kg of pure N_2O. Assuming complete atmospheric venting during technical coolant procedures, the direct environmental impact per cylinder is modeled as:

$$7.5 \text{ kg} \times 273 = 2{,}047.5 \text{ kg } CO_2\text{-eq} \tag{4}$$

2.3.5 Regulatory Gap Analysis

A regulatory gap analysis was conducted to cross-examine LUMC's current operational reality against applicable Dutch statutory laws and clinical safety requirements. Institutional workflows, ventilation protocols, and facility designs were reviewed against three distinct legislative pillars:

- **Medicines Act (*Geneesmiddelenwet*):** To evaluate compliance regarding the safe storage, handling, traceability, and pharmaceutical quality control of medical-grade gases as prescription-only substances.
- **Opium Act (*Opiumwet*):** To establish regulatory boundaries regarding strict inventory tracking and institutional security measures, accounting for the legislative reclassification of non-medicinal nitrous oxide.
- **Working Conditions Act (*Arbowet*):** To evaluate compliance with legally mandated occupational exposure limits (OELs). The current statutory standard in the Netherlands restricts maximum workplace atmospheric exposure to a time-weighted average (TWA) of 152 mg/m^3 (equivalent to 80 ppm) over an 8-hour shift, designed to safeguard healthcare personnel against reproductive and neurological health risks.

Discrepancies identified between clinical practices and these statutory obligations were categorized as infrastructural or procedural gaps.

2.3.6 Statistical Analysis

Quantitative data lines extracted from the procurement portals and track-and-trace databases were compiled, cleaned, and analyzed using Microsoft Excel (v16.0). Descriptive statistics were applied to compute cumulative institutional volumes, mean annual procurement rates, and proportional distributions of gas types across clinical departments. Temporal variations over the seven-year timeline were evaluated to isolate annual trend lines. Real-world macro equivalents for transportation and energy baselines were derived using standard environmental indicators: a passenger vehicle carbon emission baseline of 0.15 kg CO_2/km and a multi-person Dutch household combined energy footprint baseline of $3,000$ kg CO_2/year.

2.4 Results

2.4.1 Quantitative Consumption Volumes and Qualitative Utilization Patterns at LUMC

Nitrous oxide is utilized across four primary departments at the LUMC: the Emergency Department (ED), the Children's Hospital, Obstetrics and Gynecology (OBGYN), and Surgery.

On all clinical departments where N_2O is administered for analgesic or sedative purposes, delivery is managed via demand-valve flow systems manufactured by Linde Gas and Puramed. Notably, the entire medical center relies exclusively on gas cylinders for supply; there is no central infrastructure or piped pipeline network for N_2O distribution. This deliberate localized containment significantly reduces the baseline volume of gas consumption and prevents systemic pipeline leakage, which heavily contributes to institutional greenhouse gas emissions.

Procurement and inventory tracking data were analyzed to determine consumption patterns and delivery formulations across departments. Table 6 outlines the specific product type used by each unit. Relivopan consists of a premixed 50/50 ratio of nitrous oxide and oxygen designed for direct patient inhalation. Niontix comprises 100% pure liquefied N_2O, which must either be blended locally on-site prior to clinical administration or deployed in its pure state for different applications.

Department	Type of Nitrous Oxide Formulation
ED	Relivopan (50% N_2O / 50% O_2)
Children's Hospital	Relivopan (50% N_2O / 50% O_2)
OBGYN	Relivopan (50% N_2O / 50% O_2)
Surgery	Niontix (100% N_2O)

Table 6: Nitrous Oxide Formulations Utilized per Department

Clinical indications, treatment durations, and target patient demographics vary considerably across departments, as summarized in Table 7. Within the ED, Children's Hospital, and OBGYN units, N_2O is administered for its analgesic or sedative properties. Conversely, the surgical department utilizes the gas in an independent, non-sedative capacity as a localized cryoanalgesia during specialized operative procedures. Patient profiles are predominantly pediatric across the ED, Children's Hospital, and surgical cohorts, whereas the OBGYN demographic consists exclusively of adult patients. Furthermore, exposure durations differ significantly between units: the ED and Children's Hospital employ N_2O strictly for brief, transient interventions, whereas the OBGYN department requires prolonged, continuous administration throughout the active phase of labor.

Department	Type of Intervention	Target Population
ED	Short, painful acute interventions	Children, elderly patients with dementia, and individuals with intellectual disabilities.
Children's Hospital	Short, painful planned interventions	Pediatric patients exhibiting high procedural anxiety.
OBGYN	Labor analgesia (first-line response)	Peripartum women during active labor.
Surgery	pectus excavatum repair (N_2O as cryoanalgesia)	Pediatric surgical candidates.

Table 7: Clinical Interventions and Target Populations for Nitrous Oxide Use

Total institutional procurement volumes were retrieved via the central purchasing division. Tables 8 and 9 display the annual cylinder procurement volumes derived from explicit website orders alongside logged tracking data from the institutional track-and-trace inventory system.

Because Niontix is utilized exclusively for cryoanalgesia within surgical settings, all reported hospital-wide metrics for this specific product formulation correspond solely to the surgical department. As demonstrated in Table 8, Niontix consumption experienced a sharp increase starting in 2023 across both the procurement portal orders and the track-and-trace system logs, consequently driving a proportional escalation in associated environmental emissions.

	Procurement Portal Orders				Track-and-Trace System Log			
Year (NIONTIX)	**Cyl.**	**CO_2-eq (kg)**	**Driving (km)[a]**	**Homes (yr)[b]**	**Cyl.**	**CO_2-eq (kg)**	**Driving (km)[a]**	**Homes (yr)[b]**
2019	1	2.047,5	13.650	0,7	1	2.047,5	13.650	0,7
2020	0	0,0	0	0,0	0	0,0	0	0,0
2021	2	4.095,0	27.300	1,4	0	0,0	0	0,0
2022	3	6.142,5	40.950	2,0	0	0,0	0	0,0
2023	27	55.282,5	368.550	18,4	20	40.950,0	273.000	13,7
2024	35	71.662,5	477.750	23,9	23	47.092,5	313.950	15,7
2025	41	83.947,5	559.650	28,0	31	63.472,5	423.150	21,2

Notes: [a] Based on an average European passenger vehicle emission rate of 0.15 kg CO_2/km. [b] Calculated using a national benchmark of 3,000 kg CO_2/year for combined annual energy consumption in an average multi-person Dutch household.

Table 8: Annual Niontix Procurement Metrics with Integrated Environmental Carbon Equivalents

Conversely, modeling the environmental impact of Relivopan introduces greater analytical complexity, as aggregate institutional consumption metrics are distributed across three distinct clinical sectors: the ED, OBGYN, and the Children's Hospital. To establish a standardized baseline, the associated tables calculate the theoretical maximum greenhouse gas footprint by assuming an unmitigated scenario wherein 100% of the administered gas escapes directly into the biosphere.

Notably, procurement portal data presented in Table 9 indicate a lower mean volume of purchased cylinders between 2019 and 2022 compared to the 2023–2025 period. Interestingly, this temporal shift and its associated discrepancy are

completely absent from the independent track-and-trace system metrics, highlighting systemic variances between upstream purchase order logs and real-world physical inventory tracking.

	Procurement Portal Orders				Track-and-Trace System Log			
Year (RELIVOPAN)	**Cyl.**	**CO_2-eq (kg)**	**Driving (km)**	**Homes (yr)**	**Cyl.**	**CO_2-eq (kg)**	**Driving (km)[a]**	**Homes (yr)[b]**
2019	13	5.478,2	36.521	1,8	18	7.585,2	50.568	2,5
2020	12	5.056,8	33.712	1,7	11	4.635,4	30.903	1,5
2021	12	5.056,8	33.712	1,7	14	5.899,6	39.331	2,0
2022	10	4.214,0	28.093	1,4	9	3.792,6	25.284	1,3
2023	17	7.163,8	47.759	2,4	14	5.899,6	39.331	2,0
2024	18	7.585,2	50.568	2,5	18	7.585,2	50.568	2,5
2025	16	6.742,4	44.949	2,2	13	5.478,2	36.521	1,8

Notes: [a] Based on an average European passenger vehicle emission rate of 0.15 kg CO_2/km. [b] Calculated using a national benchmark of 3,000 kg CO_2/year for combined annual energy consumption in an average multi-person Dutch household.

Table 9: Annual Relivopan Procurement Metrics with Integrated Environmental Carbon Equivalents

Emergency Department (ED)
The ED utilizes Relivopan for acute, short-duration therapies. Historical delivery volumes across the ED and their integrated macro environmental equivalents are detailed in Table 10. Between 2019 and 2025, cumulative nitrous oxide consumption within this department generated an environmental footprint equivalent to $21,070$ kg CO_2-eq. This baseline matches the emissions of a standard passenger vehicle traveling approximately 70,236 km, a distance equivalent to roughly one and a half circumferences of the Earth.

Children's Hospital
Relivopan delivery in the procurement tracking shown in Table 10. The cumulative CO_2-eq emissions resulting from medical gas consumption during this observation window are geographically comparable to the emissions generated by a continuous automotive journey originating in the Netherlands, traversing the expanse of Asia, and continuing down the entire length of the Americas to reach Ushuaia, Argentina, the southernmost city on the planet.

Obstetrics and Gynecology (OBGYN)
Delivery logs and clinical utilization metrics for the OBGYN unit are presented in Table 10. Over the monitoring interval, gas consumption generated a cumulative environmental footprint of $22,334.2$ kg CO_2-eq. This baseline is equivalent to an automotive trajectory of 148,893 km driven in a standard diesel passenger vehicle, a distance corresponding to approximately 3.715 planetary circumferences.

Surgery
Within the surgical department, N_2O serves an independent, non-anesthetic role as a localized cryoanalgesia during specialized operative procedures. Logistics data presented in Table 10 demonstrate that this specific surgical procedure was introduced at the LUMC in 2023, initiating an immediate, sharp increase in institutional Niontix procurement. Over a three-year observation window, this surgical indication resulted in a cumulative environmental release of $56,440.8$ kg CO_2-eq. This greenhouse gas footprint is equivalent to an automotive transit of approximately 376,272 km, a distance roughly matching the planetary trajectory from the Earth to the moon.
To contextualize these findings within the broader institutional scope, the cumulative carbon footprint derived from medicinal nitrous oxide was benchmarked against the total greenhouse gas emissions of the LUMC. In 2019, the total institutional carbon footprint was recorded at 68,043 tonnes of CO_2, with total N_2O consumption across the four evaluated departments generating $4,214.0$ kg CO_2-eq (4.214 tonnes), representing approximately 0.0062% of the hospital's macro emissions. By 2022, total institutional emissions decreased to 51,730 tonnes of CO_2, while departmental N_2O emissions stood at $3,792.6$ kg CO_2-eq (3.793 tonnes), accounting for 0.0073% of the total institutional baseline.

	ED (Relivopan)				Children's Hosp. (Relivopan)				OBGYN (Relivopan)				Surgery (Niontix)			
Year	**Cyl.**	**CO_2 eq**	**Drv. km[a]**	**Hm yr[b]**	**Cyl.**	**CO_2 eq**	**Drv. km[a]**	**Hm yr[b]**	**Cyl.**	**CO_2 eq**	**Drv. km[a]**	**Hm yr[b]**	**Cyl.**	**CO_2 eq**	**Drv. km[a]**	**Hm yr[b]**
2019	2	842.8	5,619	0.3	2	842.8	5,619	0.3	6	2,528.4	16,856	0.8	0	–	–	–
2020	7	2,949.8	19,666	1.0	0	0.0	0	0.0	4	1,685.6	11,237	0.6	0	–	–	–
2021	5	2,107.0	14,047	0.7	2	842.8	5,619	0.3	7	2,949.8	19,665	1.0	0	–	–	–
2022	2	842.8	5,619	0.3	0	0.0	0	0.0	7	2,949.8	19,665	1.0	0	–	–	–
2023	2	842.8	5,619	0.3	1	421.4	2,809	0.1	10	4,214.0	28,093	1.4	18	15,163.2	101,088	5.1
2024	5	2,107.0	14,047	0.7	2	842.8	5,619	0.3	10	4,214.0	28,093	1.4	18	15,163.2	101,088	5.1
2025	2	842.8	5,619	0.3	2	842.8	5,619	0.3	9	3,792.6	25,284	1.3	31	26,114.4	174,096	8.7
Total	**25**	**21,070.0**	**70,236**	**3.6**	**9**	**3,792.6**	**25,281**	**1.3**	**53**	**22,334.2**	**148,893**	**7.5**	**67**	**56,440.8**	**376,272**	**18.8**

Notes: CO_2 is expressed in Calculated CO_2-eq (kg). [a] Evaluated at 0.15 kg CO_2/km. [b] Evaluated at 3,000 kg CO_2/household-year.

Table 10: Comprehensive Annual Nitrous Oxide Consumption and Environmental Benchmarks Across All Institutional Departments via Track-and-Trace System Log

2.4.2 Temporal Trends in Volume and Indications Over Seven Years

The seven-year observation period reveals distinct shifts in medical gas consumption driven by macro-environmental disruptions, structural facility renovations, and evolving clinical paradigms. When evaluating these longitudinal patterns, a prominent methodological divergence emerges between the two primary tracking frameworks for Relivopan. The central procurement database documents a lower moving average of cylinder purchases between 2019 and 2022 compared to the subsequent 2023–2025 period. Conversely, the independent track-and-trace inventory system reflects a far more stable institutional distribution of physical cylinders across these same intervals.

Across the evaluated medical centre, departmental N_2O consumption trends are heavily dictated by clinical indications, localized infrastructure, and structural or macro-environmental disruptions. Within the ED, the gas mixture is utilized for acute, short-duration therapies; despite temporary spatial transitions necessitated by extensive facility remodeling between 2021 and 2024, longitudinal consumption volumes remained highly stable. Similarly, the Children's Hospital demonstrated consistent multi-year consumption patterns, maintaining stable baseline logistics despite a temporary departmental relocation during a comprehensive outpatient clinic renovation in 2019.

Conversely, the Obstetrics and Gynecology department experienced a pronounced contraction in gas utilization around 2020. This transient decline is directly attributable to the operational disruptions of the COVID-19 pandemic, during which strict institutional protocols and hospital capacity reallocations temporarily reduced intrapartum admissions. Following this pandemic-era decline, obstetric utilization recovered steadily, establishing a sustained upward consumption trajectory.

Finally, the Surgical Department represents a distinct operational paradigm, utilizing pure liquefied N_2O as a localized cryoanalgesia agent during pectus excavatum repair procedures connected to a centralized gas scavenging system. Because this department is the exclusive institutional consumer of this pure product formulation, all macro-level hospital procurement trends for the liquefied gas map directly to this single unit. Notably, the clinical introduction of a specialized pediatric thoracic repair procedure in 2023 generated an immediate, exponential surge in gas procurement, rapidly establishing this single surgical indication as the largest and fastest-growing contributor to the institution's medical gas environmental footprint.

2.4.3 Hardware, Infrastructure, and Regulatory Compliance

The LUMC utilizes a bifurcated hardware framework to manage waste-gas mitigation and maintain compliance with statutory occupational health and safety (ARBO) exposure thresholds. Institutional mitigation strategies are broadly divided between permanent, centralized vacuum-scavenging networks and standalone, localized catalytic decomposition hardware. The centralized scavenging systems mechanically route waste gases away from clinical spaces toward dedicated mechanical infrastructure zones, whereas the mobile cracking systems decompose the gas directly within the treatment environment. A comparative structural overview of these distributed management strategies is compiled in Table 11.

Department	**Type of N_2O Management**	**Technical Location within LUMC**
ED	Central vacuum scavenging	Floor K1
Children's Hospital	Mobile catalytic cracking	Independent unit (Floor J6)
OBGYN	Central vacuum scavenging	Floor J7
Surgery	Central vacuum scavenging	Floor J5

Table 11: Distribution of Institutional Waste Gas Management Systems

Emergency Department (ED)
The ED transitioned to a permanent, centralized vacuum-scavenging infrastructure in October 2024 during the sector K2 renovation, providing active extraction ports across seven designated treatment rooms tied to a negative-pressure generation assembly on technical level K1. Prior to this structural integration, waste-gas mitigation relied on mobile catalytic decomposition units, alternating between Exidio and Medclair mobile systems. These mobile configurations imposed severe operational constraints, most notably a mandatory 30-minute warm-up cycle. Although internal guidelines mandated that these units remain permanently powered to ensure immediate clinical readiness, compliance in the fast-paced acute care environment was inconsistent. Furthermore, frequent hardware vulnerabilities required specialized manufacturer technician interventions, resulting in multi-week system downtimes.

This technical history introduces a significant confounding factor into the department's longitudinal carbon footprint modeling. Because standard unmitigated baseline calculations assume direct atmospheric venting, the theoretical values drastically overstate historical emissions; from 2019 until October 2024, active catalytic cracking rendered real-world atmospheric emissions virtually negligible. Assuming a uniform temporal distribution of gas consumption across the transitional year of 2024, the actual residual footprint is calculated at $1,194.0$ kg CO_2-eq, in stark contrast to the theoretical unmitigated baseline of $21,070.0$ kg CO_2-eq. This real-world footprint is equivalent to an automotive transit of approximately 7,959 km, a physical distance stretching from the LUMC to Beijing, China.

Children's Hospital
The Children's Hospital relies entirely on an independent catalytic cracking system, specifically a mobile Medclair unit deployed on floor J6. Qualitative assessments indicate high clinical staff satisfaction with this equipment. Although the mobile configuration imposes operational constraints, requiring a proactive 30-minute warm-up phase prior to clinical interventions, it delivers high breakdown efficiency without requiring structural modifications to the facility's central plumbing network. Methodologically, because this department utilizes an active chemical destruction framework, raw procurement volumes do not directly correlate with atmospheric release. Consequently, the standard carbon equivalent models based purely on cylinder allocation significantly overestimate the actual environmental footprint of the pediatric unit.

Obstetrics and Gynecology (OBGYN)
The OBGYN department coordinates labor analgesia using Relivopan integrated with a centralized, high-efficiency vacuum scavenging network localized to the birthing suites on floor J7. Continuous negative line pressure is maintained via a dedicated central pump assembly housed locally within the J7 technical zone, ensuring reliable and uninterrupted waste-gas extraction during prolonged obstetric interventions. In contrast to departments utilizing catalytic cracking technology, the OBGYN unit features no localized gas-destruction mechanisms. Consequently, all logged medical gas consumption within this sector translates fully and directly to the calculated atmospheric CO_2-eq footprint.

Surgery
The surgical department utilizes a localized centralized scavenging network situated on floor J5 to evacuate pure liquefied N_2O (Niontix) following its application as a cryoanalgesia. Because the central vacuum infrastructure evacuates the gas directly into the external environment without secondary chemical transformation or localized thermal decomposition, there is a direct linear correlation between procurement metrics and biosphere degradation. Thus, 100% of the reported surgical gas utilization contributes completely and unmitigated to the institutional CO_2-eq emission calculations.

2.4.4 Clinical Administration Procedures and Departmental Workflows

The three clinical departments utilizing N_2O for conscious sedation or analgesia employ distinct protocols to manage the termination of therapy and post-procedure gas removal, as structured in Table 12.

Department	Post-Procedure N_2O Termination & Scavenging Protocols
ED	5 minutes of active environmental room scavenging
Children's Hospital	5 minutes of continuous pure oxygen administration
OBGYN	20 minutes of active room scavenging and 5 minutes of oxygen administration
Surgery	Continuous extraction during cryo-coolant application

Table 12: Procedural Variations in Nitrous Oxide Discontinuation and Scavenging

Emergency Department (ED)
Given that the ED operates within an acute care framework, clinical teams prioritize rapid deployment, workflow mobility, and immediate equipment availability. The recent transition from large, mobile catalytic cracking units to a

centralized waste-gas scavenging infrastructure integrated with compact delivery carts successfully mitigated prior mobility constraints and accelerated clinical response times.

Qualitative feedback from department stakeholders, specifically, the clinical lead for medical gases within the ED, regarding the mandatory 5-minute post-procedure scavenging protocol revealed that this temporal parameter was originally instituted as a pragmatic operational buffer to clear the majority of post-treatment exhaled gas, rather than being derived from formal clinical trial data. Because cumulative procedure volumes in the ED are relatively low and individual exposure durations are brief, chronic occupational exposure for healthcare providers remains minimal. While strict adherence to the 5-minute extraction protocol varies in daily clinical practice, personnel frequently mitigate ambient exposure by maintaining physical distance from the patient immediately following the discontinuation of gas administration.

Obstetrics and Gynecology (OBGYN)
The OBGYN unit manages an unscheduled clinical workflow utilizing a centralized waste-gas scavenging network. This system has remained a stable pillar of the unit's clinical infrastructure since the reintroduction of N_2O into standard obstetric care practices.

When establishing the local safety protocol, which mandates 20 minutes of post-procedure room scavenging alongside 5 minutes of direct oxygen therapy, the department adopted an existing framework developed by the Erasmus Medical Center (Erasmus MC) in Rotterdam. Occupational safety for healthcare personnel under this Erasmus MC protocol was validated during an initial pilot study. This framework was implemented directly to ensure institutional compliance with statutory occupational health exposure limits during the pilot phase. Subsequent environmental air monitoring confirmed that this protocol effectively maintains ambient gas concentrations safely below regulatory thresholds.

Children's Hospital
The pediatric department operates on a planned, elective schedule, allowing clinical teams to easily accommodate the 30-minute warm-up requirement of the Medclair catalytic cracking unit. To minimize patient diffusion hypoxia and manage ambient waste gas, the unit utilizes a strict post-procedure protocol consisting of 5 minutes of pure oxygen administration. Staff interviews show that this protocol was modeled directly on established clinical guidelines from Maastricht University Medical Center and the Onze Lieve Vrouwe Gasthuis (OLVG) in Amsterdam, following formal training certifications completed by the clinical staff.

2.5 Discussion

The findings of this study provide a comprehensive baseline of N_2O procurement, utilization patterns, and associated environmental impacts at the LUMC. This section contextualizes these results within international healthcare sustainability frameworks, addresses the operational challenges of waste-gas mitigation, and evaluates infrastructural paths toward structural emission reductions.

2.5.1 Refining the Environmental Model: Technical Discrepancies and Residual Pressure

The absolute emissions modeled in the results section represent a theoretical maximum scenario wherein 100% of the procured volume is released unmitigated into the biosphere. For the technical application of Niontix within the surgical department, this assumption represents a highly accurate reflection of reality. The local scavenging infrastructure connects directly to the facility's general heating, ventilation, and air conditioning (HVAC) exhaust network without secondary filtration or gas-capture systems. Furthermore, procedural mandates require that Niontix cylinders be fully emptied during cryoanalgesia applications, ensuring that 100% of the procured mass is directly vented into the atmosphere.

Conversely, modeling the environmental footprint of Relivopan involves compounding technical variables and systemic data limitations. A primary limitation of the current dataset is its focus on absolute, department-level volume allocations rather than patient-specific utilization metrics, such as the exact number of patients treated and the precise duration of individual exposures. Because clinical interventions vary drastically by department, identical consumption volumes can represent fundamentally distinct clinical delivery profiles. Furthermore, localized waste-gas mitigation strategies significantly decouple absolute procurement logs from actual environmental emissions. Within the Children's Hospital, waste management relies on a mobile catalytic cracking unit capable of decomposing up to 99% of processed N_2O into inert N_2 and O_2 molecules [104]. In this configuration, the real-world carbon footprint is governed by user mask compliance and gas-capture efficiency rather than raw cylinder volume.

A similar operational discrepancy occurs within the ED, where the unmitigated carbon model drastically overstates historical emissions due to an infrastructural transition in October 2024. Prior to this shift to a centralized vacuum-scavenging system, the ED utilized active catalytic cracking units. Consequently, instead of releasing the theoretical baseline of $21,070.0$ kg CO_2-eq into the biosphere, the ED's true historical output over that period is estimated to be approximately $1,194.0$ kg CO_2-eq, if in the year 2024 N_2O use is evenly distributed. This adjustment fundamentally scales down the macro-environmental impact analogy from one and a half planetary circumferences to an automotive

transit from the LUMC extending to the antipodal waters near New Zealand, highlighting how localized destruction infrastructure heavily influences departmental footprints.

An additional technical variable involves the management of cylinder residual pressure. Clinical safety protocols conventionally dictate that gas cylinders must not be completely exhausted; instead, a safety threshold of residual pressure is maintained inside the cylinder to protect against atmospheric moisture contamination. However, logistics tracking and consultation with manufacturing stakeholders confirm that this remaining gas is neither reclaimed nor catalytically neutralized during commercial recycling loops. Instead, it is standard practice to vent this residual volume directly to the atmosphere at external gas purification hubs prior to refilling. Notably, qualitative assessments indicate a variable understanding of this protocol among frontline healthcare providers, with some staff members occasionally exhausting cylinders entirely until a physical vacuum effect occurs at the patient interface. Ultimately, because the unconsumed residual volume is eventually vented by the distributor, treating the entire pre-filled mass of a cylinder as a direct atmospheric emission remains mathematically valid for institutional carbon accounting, regardless of whether the gas is spent at the bedside or discharged at an external facility.

Although N_2O constitute a minor fraction of the facility's aggregate carbon footprint, which is heavily dominated by energy consumption, their exceptionally high global warming potential positions them as high-leverage targets for targeted clinical mitigation strategies.

2.5.2 Temporal Disruptions and the Post-Pandemic Baseline

Longitudinal analysis of the seven-year timeline requires careful accounting for macroeconomic disruptions, most notably the COVID-19 pandemic. Between 2019 and 2022, strict hospital guidelines enforced the suspension of non-urgent elective procedures to preserve intensive care and emergency capacities [105].

This suppression of regular clinical volumes directly skewed historical consumption data, creating an artificially low emissions footprint. Post-2022 trends reveal a clear rebound effect, establishing a higher, more structurally accurate baseline of healthcare delivery. This stabilization was fundamentally shifted in 2023 by the introduction of the pectus excavatum repair technique within the Surgery department. This single operational pivot demonstrates that clinical innovations can drastically alter an institution's carbon path independently of general hospital occupancy rates.

The discrepancy between the Relivopan track-and-trace registry and the central procurement database highlights how order-placement frequencies often decouple from real-world clinical demand due to fluctuating stockpiling behaviors and institutional supply-chain adjustments. The localized operational drivers and longitudinal trends underlying these metrics are detailed by clinical department below.

2.5.3 Mitigation Strategies: Volumetric Reduction versus Technological Abatement

To reconcile clinical utility with sustainability objectives, LUMC faces two primary pathways: reducing absolute clinical consumption or scaling technical degradation systems. Volumetric containment has already been advanced through the deployment of cylinder-bound supply lines and demand-valve flow systems. Further systematic reductions require targeted clinical audits within individual departments to evaluate the clinical efficacy of alternative therapies and overcome behavioral resistance to workflow changes [106].

Alternatively, technological abatement can be achieved by expanding gas-capture infrastructure. However, the choice between mobile cracking units and centralized abatement systems involves complex operational trade-offs, as outlined below:

- **Mobile Catalytic Cracking Units:** While highly effective in the Children's Hospital due to an organized, elective scheduling framework, mobile cracking units present major operational barriers in high-throughput acute settings. As demonstrated by the recent abandonment of mobile units in the ER, these systems introduce a mandatory 30-minute warm-up latency, possess a cumbersome physical footprint that restricts crowded bed spaces, and exhibit high mechanical failure rates that cause extended downtime. These factors create significant resistance among acute clinical staff who prioritize immediate workflow deployment.

- **Centralized Abatement Systems:** A centralized catalytic destruction system represents an architecturally viable alternative, particularly because active vacuum scavenging lines are already structurally installed across the ER, OBGYN, and Surgery units. Centralized systems eliminate bedside warm-up delays and remove physical hardware clutter from treatment rooms. However, centralized installations demand substantial upfront capital expenditures and require continuous electrical power to maintain thermal destruction temperatures [104]. For low-volume departments, the continuous power consumption of a central system may create an energy demand that offsets a portion of its carbon offset value.

To determine the fiscal and environmental viability of a centralized system, future engineering studies must quantify the exact ratio of waste gas successfully captured within scavenging lines versus the volume lost to general room ventilation.

Emergency Department (ED)
Between 2019 and 2025, cumulative nitrous oxide procurement within the ED generated a theoretical maximum environmental footprint of 21,070 kg CO_2-eq, matching the emissions of a standard passenger vehicle traveling 70,236 km (approximately 1.5 planetary circumferences). While the department operated temporary mobile destruction units earlier in this timeline, persistent hardware vulnerabilities often led to extended system downtimes. Consequently, following the integration of a permanent centralized vacuum-scavenging infrastructure in October 2024, 100% of the evacuated waste gas is now routinely vented unmodified into the atmosphere, validating this unmitigated calculation model for institutional carbon accounting. Remarkably, a mere two-year subset of this consumption releases greenhouse gas volumes sufficient to simulate an automotive transit extending from the LUMC to the antipodal waters of the South Pacific Ocean, just off the coast of New Zealand.

Children's Hospital
The cumulative CO_2-eq emissions derived from raw pediatric gas procurement during the analyzed window are geographically comparable to the emissions generated by a continuous automotive journey originating in the Netherlands, traversing the expanse of Asia, and continuing down the entire length of the Americas to reach Ushuaia, Argentina, the southernmost city on the planet. Crucially, this comparison serves as an unmitigated baseline; the actual atmospheric impact of the department was dramatically lower in reality. Because the pediatric ward relies on a dedicated mobile cracking unit with a stable multi-year operational presence, up to 99% of the processed N_2O was actively decomposed into inert N_2 and O_2 before escaping into the biosphere.

Surgery
From an environmental perspective, the cryoanalgesia process utilized during pectus excavatum repairs could technically be transitioned to alternative CO_2 cryo-systems. While such a transition would inherently result in direct CO_2 emissions, the strategy remains compelling due to the significantly lower GWP of CO_2 relative to N_2O. Alternatively, retaining the existing N_2O delivery framework in combination with a high-efficiency catalytic cracking system could theoretically reduce residual emissions down to a mere 1%. Operationalizing either strategy remains clinically and financially constrained by infrastructure requirements, as the current surgical apparatus is strictly engineered for unmitigated N_2O use. Ultimately, further comparative research and lifecycle emissions modeling are required to determine precisely which technological configuration yields the absolute lowest net atmospheric carbon contribution.

2.5.4 Regulatory Compliance, Ventilation, and Occupational Safety Gaps

From an occupational health perspective, LUMC maintains a highly controlled closed-loop HVAC environment. To guarantee staff safety and mitigate risks in the event of hardware failure, clinical spaces utilizing N_2O feature elevated air exchange rates, such as a mandated hourly ventilation factor of four ($4\times$) within pediatric outpatient rooms [107, 108].

While individual clinical spaces are equipped with either active scavenging ports or mobile cracking devices, a critical compliance gap remains unresolved: the true ratio of escaped waste gas evacuated through source-capture scavenging versus the volume diluted and drawn into general HVAC ventilation lines is currently unmonitored.

This tracking deficit represents an operational vulnerability relative to the strict statutory occupational exposure limit (OEL) of 152 mg/m^3 (80 ppm) enforced under the Dutch Working Conditions Act (*Arbowet*) [109]. Without empirical real-time air monitoring, compliance with these time-weighted exposure targets cannot be definitively verified.

Addressing this gap requires the integration of ambient gas monitoring networks. Currently, institutional hesitation from facility infrastructure departments regarding third-party vendor maintenance structures acts as a barrier to deployment. Overcoming these logistical bottlenecks is a critical prerequisite for achieving transparent regulatory compliance, validating employee safety, and accurately quantifying institutional carbon accounting.

2.5.5 Comparison of Administration Procedures

An analysis of departmental administration workflows reveals substantial procedural variation regarding post-treatment gas elimination and scavenging durations. Before examining these institutional differences, a brief overview of the pharmacokinetic profile of Relivopan (50% N_2O / 50% O_2) is warranted to contextualize the clinical rationale behind each protocol. Due to its low blood-gas partition coefficient, N_2O is characterized by rapid pulmonary uptake: sedative onset occurs within 2 to 3 minutes of inhalation, with peak blood concentrations reached after approximately 5 minutes [110]. Upon cessation of administration, the elimination profile mirrors this rapid kinetics. Sedative effects resolve within 3 to 5 minutes of mask removal, during which the vast majority of the inhaled gas volume is exhaled via pulmonary excretion. Complete physiological elimination is achieved within 10 to 15 minutes [110]. Regarding diffusion hypoxia, the risk associated with the 50/50 formulation differs meaningfully from that of higher-concentration N_2O regimens. Clinical studies have demonstrated that healthy patients administered a 50:50 N_2O/O_2 mixture do not exhibit clinically significant arterial hypoxemia following mask removal, even when resuming room air breathing, with oxygen saturation declining by approximately 2% on average before stabilizing [**Stewartetal1986**, 111]. This is attributable to the elevated baseline inspired oxygen fraction inherent to the 50/50 formulation, which provides

sufficient oxygen reserve to buffer the transient alveolar dilution caused by outward N_2O diffusion. Nevertheless, supplemental oxygen administration following cessation remains advisable in patients with compromised pulmonary or cardiac reserve [112].

The ED utilizes the least risk-averse protocol, enforcing a concise 5-minute active scavenging window immediately following the cessation of N_2O therapy. Historical pilot assessments utilizing spot-check atmospheric sampling within the ED reported occupational exposure levels within safe thresholds. However, this clinical safety margin may be highly dependent on the transient nature of ED interventions, which are strictly limited to short-duration acute procedures. If the clinical scope of the ED expands to include longer interventions requiring prolonged gas delivery, this brief evacuation window may prove insufficient, potentially exposing healthcare personnel to ambient gas concentrations that exceed statutory occupational exposure limits [111].

Conversely, the OBGYN department maintains the most risk-averse protocol within the institution. This framework mandates a 20-minute post-procedural scavenging period, embedded with 5 minutes of continuous pure oxygen (O_2) co-administration. This conservative model was adapted directly from the 2016 clinical guidelines established at the Erasmus Medical Center [113]. Given the pharmacokinetic properties described above, such an extended clearance window may be unnecessarily restrictive. Pharmacokinetic data indicate that sedative effects resolve and initial pulmonary excretion is largely complete within 4 to 5 minutes of mask removal [110]. While this suggests that the OBGYN protocol could be safely shortened to optimize delivery workflows, any reduction in scavenging time must be validated through formal, empirical clinical testing to guarantee staff safety.

Finally, the Children's Hospital employs a protocol modeled after frameworks used at Maastricht University Medical Center and the Onze Lieve Vrouwe Gasthuis (OLVG) [114, 115]. Mandating 5 minutes of combined oxygen administration and active scavenging, this protocol is inherently more risk-averse than the ED workflow due to the physiological "washout" effect. Administering pure O_2 accelerates pulmonary diffusion clearance, displacing residual N_2O from the bloodstream and reducing patient-exhaled ambient emissions inside the treatment room [112]. Furthermore, because institutional authorization to administer N_2O within the pediatric department is restricted to a small, highly specialized cohort of trained practitioners, protocol compliance is exceptionally strictly monitored and maintained compared to higher-throughput acute environments.

2.5.6 Institutional Governance and Departmental Accountability

Within the LUMC, individual clinical departments retain autonomous authority over whether to implement N_2O therapy, as well as the specific operational frameworks, including hardware selection and clinical protocols, governing its use. This localized autonomy results in considerable institutional heterogeneity regarding medical gas management across the facility. To streamline oversight, the institution utilizes an anesthetic gases committee, a multidisciplinary panel comprising diverse stakeholders from procurement, the Environmental Health and Safety department (VGM), and staff anesthesiologists, tasking them with formulating balanced, evidence-based policies regarding gas consumption.

However, a critical limitation of this governance model is the absence of frontline healthcare professionals who actively administer N_2O within the committee's roster. Consequently, strategic institutional policies are frequently designed without the direct input of practical clinical expertise. This governance gap is particularly pronounced in the obstetric unit; here, N_2O analgesia is primarily administered by primary-care midwives who are not formally employed by the university medical center. Yet, the administrative and financial responsibility for the underlying scavenging infrastructure and hardware delivery mechanisms remains strictly centralized within the LUMC, demonstrating a clear decoupling of clinical execution from institutional governance.

2.5.7 Regulatory Frameworks and Occupational Safety Compliance

Due to the well-documented health hazards associated with occupational exposure to N_2O, stringent statutory frameworks, such as the Dutch Working Conditions Act (ARBO), strictly regulate its clinical application to safeguard healthcare personnel. Within the hierarchy of industrial hygiene and risk mitigation, source reduction or complete elimination represents the most effective strategy to ensure workplace safety. This proactive minimization directly aligns with the highest tiers of the circular economy "R-ladder" framework (specifically, Refuse and Reduce), thereby positioning volume reduction as a cornerstone of an inherently sustainable institutional policy.

2.5.8 International Comparisons: The United Kingdom Perspective

In the United Kingdom (UK), medical N_2O is utilized on a substantially larger scale and under fundamentally distinct operational conditions compared to the Netherlands. First, UK healthcare facilities frequently rely on centralized manifold pipeline distribution networks rather than localized, cylinder-based supply frameworks. This architectural configuration contributes to significantly elevated fugitive emissions due to chronic, systemic pipeline leakage within hospital building structures. Furthermore, gas administration is predominantly executed via continuous-flow delivery systems rather than demand-valve mechanisms, which inherently escalates the volume of unabsorbed waste gas escaping into the environment.

The profound environmental severity of this infrastructure divergence is empirically validated by comparative Life Cycle Assessment (LCA) data. A landmark cradle-to-grave LCA study contrasting obstetric pathways in the

UK and the Netherlands demonstrated that the clinical implementation of N_2O acts as a massive carbon multiplier; while an unmedicated vaginal hospital delivery in the UK generates a baseline footprint of just 12.47 kg CO_2-eq, the introduction of an unmitigated nitrous oxide/oxygen mixture expands total intrapartum emissions to an alarming 237.33 kg CO_2-eq per delivery [116]. This 25-fold escalation makes unabated gas administration the single largest variable governing obstetric carbon footprints, highlighting an urgent clinical need for alternative analgesia routing or centralized nitrous oxide destruction systems [116].

Clinical and occupational safety protocols are also considerably less comprehensive than contemporary Dutch standards. For instance, frontline personnel are often not required to undergo mandatory specialized training for gas administration, and pre-procedural screening for patient contraindications, such as vitamin B_{12} deficiency, is largely absent from routine workflows. Crucially, active waste-gas scavenging networks or catalytic decomposition systems are rarely deployed in these settings. This infrastructure deficit compromises institutional sustainability initiatives and increases occupational health risks by exposing clinical staff to elevated ambient gas concentrations. This operational landscape closely mirrors the historical status of the Netherlands one to two decades ago; however, Dutch clinical practices have since transformed through systematic optimizations in delivery technologies, waste processing, and regulatory compliance. Consequently, the proven infrastructural and procedural strategies implemented in the Netherlands serve as an instructive, highly translatable template for international healthcare systems seeking to de-carbonize their clinical operations.

2.5.9 Strategic Recommendations for Institutional Policy and Infrastructure

To optimize occupational safety and advance institutional sustainability goals, three strategic interventions are recommended across the facility's administrative and structural frameworks:

First, while occupational exposure monitoring is routinely conducted within clinical patient-care zones to ensure compliance with statutory ARBO standards, this environmental surveillance should be systematically extended to technical and maintenance infrastructure zones. Technical sectors house the continuous pipeline networks, manifolds, and extraction pumps of the centralized scavenging systems. Because localized, low-level leakage is a documented operational vulnerability in pressurized medical gas distribution systems, unchecked gas accumulation poses a hidden occupational health hazard to maintenance personnel who occupy these service environments throughout the day. Extending routine air sampling to these technical zones is imperative to ensure comprehensive regulatory compliance.

Second, regarding future capital infrastructure investments, if the institution evaluates the deployment of new waste-gas mitigation systems, prioritizing a centralized catalytic cracking installation for the surgical department offers the greatest numerical margin for quantitative CO_2-eq reduction. However, an even higher-leverage mitigation strategy would be addressing the source of emissions directly by transitioning the pediatric *pectus excavatum* repair framework from a nitrous oxide-based cryoanalgesia to a compressed CO_2 technical alternative. This transition would permanently eliminate the associated global warming potential of the procedure without relying on secondary waste-capture systems.

Finally, the institution should establish formal, cross-functional channels of communication to bridge the current governance gap between policy and practice. Frontline healthcare providers who actively administer N_2O, including primary-care midwives and emergency clinicians, must have direct, structured representation within the institutional anesthetic gases committee. Fostering collaborative dialogue between operational end-users and administrative decision-makers will ensure that future infrastructure investments, safety protocols, and sustainability policies are practically viable, clinically sound, and aligned across all organizational levels.

While technical and procedural mitigation parameters vary across the general hospital wards, the unique operational workflows, capacity demands, and clinical conversion paths of the Obstetrics department warrant a dedicated institutional deep dive, which is explored in the subsequent chapter.

3 Clinical Deep Dive: Obstetrics (LUMC)

3.1 Introduction

At the LUMC, the administration of N_2O for labor analgesia is strictly reserved for primary care midwives. Within this clinical setting, N_2O represents the sole pharmacological intervention available to primary care providers, provided they have completed the mandatory certification and training. Alternative non-pharmacological interventions utilized by these practitioners include Transcutaneous Electrical Nerve Stimulation (TENS), specialized breathing techniques, and maternal positioning. Due to safety regulations regarding the mitigation of occupational exposure, N_2O administration is confined to the hospital environment where specialized scavenging systems are operational; consequently, its use in home-birth settings is prohibited [117].

The logistical utility of N_2O becomes particularly evident during periods of high bed occupancy in secondary care. When the transition from primary to secondary care is delayed due to capacity constraints, primary care midwives may utilize N_2O as an interim measure to manage pain and stabilize the patient. As the only pharmacological analgesic within the primary care scope of practice, N_2O serves a critical role in clinical throughput and resource management within the obstetrics department.

Main Question: What is the clinical impact of N_2O use in the LUMC obstetrics department, specifically regarding analgesic success and conversion rates?

1. What is the frequency and duration of N_2O (e.g., Relivopan) administration at LUMC, and what are the associated CO_2 emission levels?
2. What is the rate of conversion from N_2O to more invasive analgesia, such as epidural anesthesia or remifentanil Patient-Controlled Analgesia (PCA)?
3. What are the projected clinical and logistical consequences of a total withdrawal of N_2O availability from the obstetrics department?
4. How do the clinical protocols, operational parameters, and regulatory frameworks governing obstetric nitrous oxide (N_2O) administration in the United Kingdom differ from contemporary Dutch practices?

3.2 Theoretical Framework

Nitrous oxide is established as a safe analgesic for both the mother and the fetus. Systematic reviews and international clinical guidelines consistently classify N_2O as a low-risk intervention [118, 119]. Maternal safety is supported by evidence indicating that N_2O is non-invasive and does not interfere with the physiological progress of labor or uterine contraction frequency [120]. Common side effects, namely nausea (13%), dizziness (5%), and drowsiness (4%), are typically transient and resolve rapidly upon cessation of inhalation [121].

From a neonatal perspective, although N_2O crosses the placental barrier, it is cleared rapidly via the neonate's respiratory system. Current literature indicates no significant association between N_2O use and central nervous system depression, adverse Apgar scores, or abnormal umbilical cord blood gas values [118].

Despite its favorable safety profile, three primary concerns persist in modern literature:

- Metabolic Impact: Nitrous oxide inhibits methionine synthase, which can lead to neurological complications in patients with pre-existing Vitamin B_{12} deficiency. Recent findings suggest N_2O may serve as a risk factor for infant B_{12} deficiency, as evidenced by elevated homocysteine levels in newborn screenings [122].
- Occupational Safety: Chronic exposure to N_2O poses reproductive and neurological risks to healthcare personnel. Therefore, the use of high-efficiency scavenging systems is a prerequisite for its administration in hospital settings [123].
- Sustainability: Nitrous oxide is a potent greenhouse gas with a significantly higher carbon footprint compared to alternative analgesic methods [123].

Parenteral opioids remain a common alternative due to their low cost and ease of administration; however, their systemic nature introduces complications not present with N_2O [124]. Unlike the rapid onset and offset of N_2O, opioids exhibit prolonged half-lives, frequently resulting in maternal sedation, nausea, and lightheadedness [125, 118].

The most significant clinical concern regarding opioid administration is maternal respiratory depression, and it can also lead to neonatal respiratory despression. Opioids cross the placenta and may neonatal resuscitation or the administration of reversal agents (e.g., Naloxone) if delivery occurs shortly after administration [125, 124]. Furthermore, opioid exposure has been linked to impaired neurobehavioral responses in the neonate, potentially disrupting the initiation of breastfeeding [126, 118].

In contrast to the dense sensory blockade provided by neuraxial techniques, the clinical utility of N_2O is characterized by its dissociative properties rather than total antinociception. Nitrous oxide facilitates a state of relaxed detachment, allowing the parturient to manage the psychological burden of labor pain without the loss of motor function or maternal agency [24]. This distinction is critical for patient counseling; women with a prior history of epidural anesthesia may perceive N_2O as sub-therapeutic if their clinical expectation is the total abolition of pain [127].

Epidural analgesia remains the gold standard for pain relief, yet it necessitates a significant increase in clinical surveillance and introduces specific physiological trade-offs. While providing superior pain scores, the resulting motor blockade often restricts maternal mobility, a sharp contrast to the non-invasive, "mobile" nature of N_2O [47]. Furthermore, the transition to epidural anesthesia involves risks absent in N_2O administration, most notably maternal hypotension, pruritus, intrapartum pyrexia, and the potential for a patchy or inadequate block [47, 128]. Consequently, the choice between these modalities involves a clinical balancing of the desire for maximum analgesic efficacy against the maintenance of physiological labor and maternal autonomy.

3.3 Methods

3.3.1 Study Design and Setting

This study was executed as a mixed-method research design, combining a retrospective cohort registry analysis with a prospective observational framework. The clinical setting was localized within the Department of Obstetrics and Gynecology at the LUMC, an academic tertiary care facility in the Netherlands. The department operates under a dual-tier care delivery model, maintaining a clear structural division between primary care (midwife-led, low-risk intrapartum management) and secondary/tertiary care (obstetrician-led, high-risk or escalated intrapartum management).

3.3.2 Population and Participant Selection

The study population comprised all pregnant individuals who received medicinal N_2O analgesia during labor between December 10, 2018, and April 15, 2026. As this is a retrospective study, no prospective selection criteria were applied; rather, receipt of nitrous oxide itself defined inclusion. Nitrous oxide was administered exclusively in the context of low-risk, singleton, cephalic pregnancies at full term ($\geq$ 37 weeks of gestation), under the care of primary-care first-line midwifery services, and only upon voluntary election by the patient as the primary pharmacological intrapartum analgesic. All individuals who received N_2O under these conditions were therefore included in the analysis.

Individuals were not included where nitrous oxide was not administered, which in practice corresponded to cases involving a documented maternal history of vitamin B_{12} deficiency or related metabolic disorders, immediate secondary- or tertiary-care admission upon presentation due to high-risk obstetric comorbidities, or indication for an elective or planned pre-labor cesarean section.

For every primary-care delivery where N_2O was deployed, a standardized clinical registry form was completed at the bedside by the attending midwife for quality-of-care auditing and statutory insurance billing compliance. This retrospective registry yielded an aggregate database of 403 distinct labor episodes, of which contained documentation for absolute departmental administration and environmental tracking.

3.3.3 The Intervention: N_2O Administration Protocol

Medicinal nitrous oxide was administered via a mobile, self-contained delivery system utilizing a premixed gas formulation consisting of 50% N_2O and 50% O_2, commercially distributed under the trade name Relivopan. The structural, clinical, and logistical steps governing the initialization, execution, and subsequent decommissioning of the mobile delivery apparatus were standardized according to institutional safety guidelines.

3.3.4 Clinical Governance and Provider Competency Frameworks

To maintain compliance with the Dutch Working Conditions Act (*Arbowet* regulations), the administration of N_2O was strictly restricted to primary-care midwives who held active institutional clinical privileges at the LUMC. Prior to obtaining clinical authorization to operate the delivery systems, all frontline midwifery personnel were legally required to complete a standardized, multi-modal competency certification pipeline. This educational pathway mandated the successful completion of an asynchronous e-learning curriculum, a written theoretical examination focusing on industrial hygiene and gas pharmacology, a supervised hands-on technical tutorial covering the hardware assembly, troubleshooting, and deconstruction of the mobile cart, and a final practical peer-reviewed clinical competency assessment at the bedside.

3.3.5 Data Collection and Source Systems

Clinical and demographic variables were compiled via electronic health record (EHR) extraction utilizing the institution's primary clinical databases (The localized *Partus-log* obstetric sub-registry). The compiled dataset was

structured around specific independent and dependent variables:

- **Independent Variables:** Cumulative duration of continuous gas exposure (minutes), maternal chronological age at the time of delivery (years), and maternal parity status (categorized dichotomously as primiparous [*primi*] or multiparous [*mult*]).
- **Dependent Variables and Clinical Outcomes:** Incidence of analgesic care escalation to secondary workflows; type of secondary intervention administered (regional epidural analgesia [EDA] or intravenous remifentanil patient-controlled analgesia [PCA]); patient-reported pain intensity variations quantified pre- and post-intervention via a validated 0–10 Visual Analog Scale (VAS).
- **Sustainability and Macro Emissions Data:** Total environmental carbon footprints, expressed in kilograms of carbon dioxide equivalents (kg CO_2-eq), were derived using consumption mass-balance metrics. Calculations utilized data reflecting a total institutional consumption of 44 pre-filled cylinders across 383 tracked administrations between 2020 and 2025, evaluating raw gas mass displacement against a standardized GWP coefficient for unmitigated direct atmospheric venting.

3.3.6 Outcome Measures and Operational Definitions

The primary clinical outcome was defined as the formal rate of analgesic conversion. This metric was operationalized as the direct, intended transition of a patient from primary midwife-led N_2O management to secondary obstetrician-led care for more invasive regional or systemic pharmacological interventions ($n = 69$).

An analgesic conversion was classified as an primary clinical failure of the initial N_2O intervention when the transfer of care was directly precipitated by an inability to achieve adequate maternal pain control or due to a documented diagnosis of non-progressive labor (failure to progress during active cervical dilation) within active utilization windows. Logistical confounding factors were defined as institutional operational constraints, including acute labor ward bed-capacity strain, temporary staff unavailability, or rapid shifts in midwifery coverage allocations that altered standard care delivery pathways.

3.3.7 Statistical Analysis

Quantitative data processing and statistical modeling were performed using Google Colab and Excel for Mac (Version 16.109.2). For all continuous parameters (e.g., duration of gas inhalation, maternal age, qualitative satisfaction values, and raw VAS point differentials), data distributions were evaluated for normality using Shapiro-Wilk testing and visual histogram analysis, and are reported as mean ± standard deviation (SD) alongside observed minimum-to-maximum ranges. Categorical data (e.g., clinical efficacy classifications, parity groups, and primary conversion indications) are expressed as absolute counts (n) and relative percentages (%).

3.4 Results

3.4.1 Frequency, Duration, and Carbon Intensity of Nitrous Oxide Administration

Nitrous oxide (N_2O, formulated as Relivopan) is administered as a primary labor analgesia modality within the maternity ward at the LUMC. The longitudinal clinical dataset analyzed spans from December 10, 2018, through April 15, 2026, with 403 labors as datapoints. Figure 6 illustrates the chronological frequency of gas administrations aggregated on a quarterly basis over this observation window. In total, clinical intake data were compiled across 21 distinct primary-care midwifery clinics operating within the institutional network.

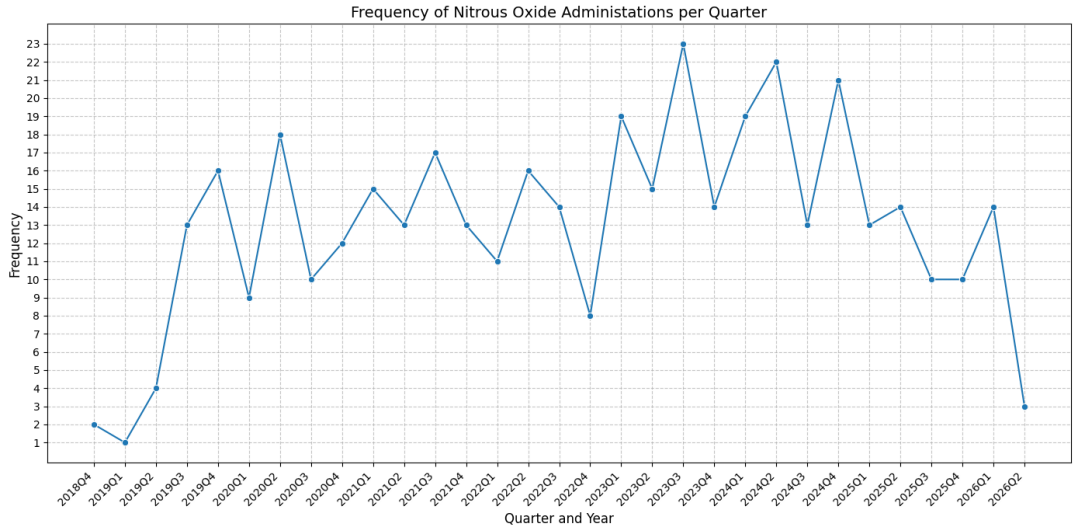

Figure 6: Frequency of Nitrous Oxide Administrations over time (quarterly)

Evaluation of clinical utility and qualitative perception metrics demonstrated high baseline satisfaction among both patients and clinical operators (Table 13). The mean client satisfaction score was 7.31 ± 2.16 on a standardized [0–10] visual analog scale, while healthcare provider satisfaction was recorded at 7.76 ± 1.88.

Category	**Average Outcome ± SD**
Client satisfaction	7.31 ± 2.16 [0–10]
Healthcare provider satisfaction	7.76 ± 1.88 [0–10]
Duration of administration	56.19 ± 45.16 minutes

Table 13: Primary clinical outcomes including satisfaction scores and administration duration

The corresponding annual gas mass allocation, consumption intensities, and subsequent environmental footprint calculations for the OBGYN department are tracked longitudinally in Table 14. Over the multi-year observation matrix, a cumulative institutional total of 44 gas cylinders were allocated to the department, facilitating 383 documented patient administrations between 2020 and 2025, and culminating in a total unmitigated greenhouse gas release of 22,325.35 kg CO_2-eq.

To contextualize these figures within tangible clinical and public health frameworks, the average carbon intensity was translated into real-world mobility and domestic energy benchmarks. On an individual micro-level, the environmental burden per single delivery varied substantially across the reporting years due to fluctuations in clinical administration durations and utilization efficiency. For instance, the carbon footprint per birth in 2020 reached a baseline low of 34.4 kg CO_2-eq, which equates to a passenger vehicle driving distance of 229.3 km, roughly equivalent to a one-way trip from the LUMC to Cologne, Germany. Conversely, the average emission intensity per delivery surged to a peak of 82.4 kg CO_2-eq in 2025. This single-birth emission profile is equivalent to a driving distance of 549.3 km, which represents a cross-border journey extending from the LUMC across Germany to Strasbourg, France, or a complete round-trip journey from Leiden to Groningen and back (∼420 km) with an additional regional transit buffer. Throughout the typical intermediate years (2022–2024), a single nitrous oxide-assisted delivery generated a mean displacement equivalent of approximately 370 to 400 km, mirror-imaging a one-way automotive commute from the LUMC to Paris, France (∼460 km) or Frankfurt, Germany (∼425 km).

On a macroscopic level, the cumulative aggregate of the department's emissions presents a severe ecological footprint. The total institutional driving distance equivalent compiled over the tracking period reached a striking 148,835.7 km. This cumulative distance is mathematically equivalent to driving a passenger vehicle around the entire

equatorial circumference of the Earth (∼40,075 km) approximately 3.7 times. Over the same multi-year timeline, the cumulative emissions from the OBGYN department matched the total annual energy and gas consumption footprint of 7.44 average Dutch multi-person households combined, highlighting a critical target area for institutional sustainability interventions and waste mitigation protocols within the obstetric theater.

			Per Single Delivery / Birth				Annual Department Total		
Year	**Total Cyl.**	**Nitrous Oxide Births**	**Administration Duration ± SD (min)**	**Mean CO_2-eq ± SD (kg)**	**Driving (km)[a]**	**Homes (yr)[b]**	**CO_2-eq (kg)**	**Driving (km)[a]**	**Homes (yr)[b]**
2019	6	34	68.18 ± 59.47	74.3 ± 21.5	495.3	0.02	2,527.73	16,851.5	0.84
2020	4	49	54.78 ± 32.81	34.4 ± 11.2	229.3	0.01	1,684.20	11,228.0	0.56
2021	7	58	54.18 ± 45.02	50.8 ± 14.7	338.7	0.02	2,948.78	19,658.5	0.98
2022	7	49	51.78 ± 42.71	60.2 ± 18.1	401.3	0.02	2,947.34	19,648.9	0.98
2023	10	71	54.48 ± 42.92	59.4 ± 16.8	396.0	0.02	4,215.23	28,101.5	1.41
2024	10	75	52.18 ± 39.78	56.1 ± 15.3	374.0	0.02	4,211.12	28,074.1	1.40
2025	9	47	61.85 ± 50.59	82.4 ± 24.6	549.3	0.03	3,790.96	25,273.1	1.26
Total	**44**	**383**	–	–	–	–	**22,325.35**	**148,835.7**	**7.44**

Notes: [a] *Evaluated at an average passenger vehicle emission rate of 0.15 kg CO_2/km.* [b] *Calculated using a national benchmark of 3,000 kg CO_2/year for the combined annual energy usage of an average multi-person Dutch household.*

Table 14: Annual Relivopan Cylinder Allocations, Clinical Administration Durations, and Multi-Level Environmental Carbon Intensity Benchmarks within the OBGYN Department for Nitrous Oxide

To evaluate the clinical efficacy of the gas mixture prior to any potential secondary interventions, changes in patient-reported pain intensity were quantified using the VAS. Across the total evaluated population, the global mean reduction in the VAS score following gas administration was 1.63 ± 1.48 points. When analyzed by parity, primiparous patients exhibited a mean VAS score decrease of 1.59 ± 1.36 points, while multiparous patients achieved a comparable mean reduction of 1.63 ± 1.62 points. Notably, tracking compliance for pain scores was incomplete, with baseline or post-procedural VAS metrics missing from 30.27% of total registry files. The localized interaction between the absolute duration of gas delivery and the corresponding post-treatment shift in pain metrics is visualized via the scatterplot in Figure 7.

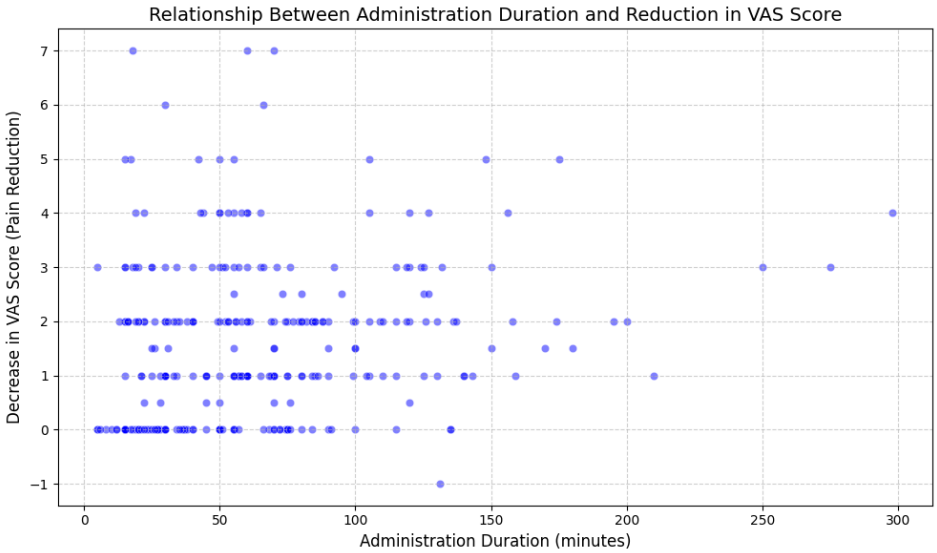

Figure 7: Scatterplot mapping the duration of nitrous oxide administration against corresponding decreases in Visual Analog Scale (VAS) pain scores

3.4.2 Conversion Rates to Secondary Analgesia and Pain Alleviation Efficacy

A critical performance metric of N_2O administration within obstetric workflows is the rate of conversion to secondary, more invasive clinical pain management modalities, such as epidural anesthesia or remifentanil patient-controlled analgesia (PCA). Analysis of the longitudinal dataset reveals an overall conversion rate of $18.35\% \pm 0.39\%$ across all recorded N_2O-assisted deliveries. This transition represents a clinically meaningful escalation in care, necessitating the formal transfer of obstetric responsibility to second-line institutional medical staff and introducing the administrative use of systemic opioids or regional blocks.

Chronological trends tracking institutional delivery volumes, primary care distributions, and total annual conversions from 2020 through 2025 are systematically cataloged in Table 15.

Year	Total Deliveries	Clinical Deliveries (%)[a]	Primary Care Deliveries (LUMC) (%)[a]	Nitrous Oxide Deliveries	Conversion to EPI/Remifentanil (%)[b]
2020	2,840	2,468 (86.9%)	372 (13.1%)	49	8 (16.3%)
2021	2,945	2,492 (84.6%)	453 (15.4%)	58	8 (13.8%)
2022	2,758	2,314 (83.9%)	444 (16.1%)	49	4 (8.2%)
2023	2,685	2,234 (83.2%)	451 (16.8%)	71	16 (22.5%)
2024	2,653	2,223 (83.8%)	430 (16.2%)	75	14 (18.7%)
2025	2,657	2,244 (84.5%)	413 (15.5%)	46	8 (17.4%)

Notes: [a] *Percentage calculated relative to total annual obstetric deliveries.* [b] *Conversion rate represents the proportion of nitrous oxide administrations that ultimately required escalation to secondary epidural (EPI) or Remifentanil analgesia.*

Table 15: Obstetric delivery statistics: longitudinal trends in volume, clinical breakdowns, primary care at LUMC, nitrous oxide utilization, and subsequent analgesic conversions (2020–2025)

Stratification of the registry data demonstrates that analgesic conversion rates varied significantly based on maternal parity, as presented in Table 16. Primiparous patients exhibited a substantially higher care escalation rate of 25.37% ($n = 51$), whereas multiparous individuals demonstrated a lower conversion rate of 9.52% ($n = 16$). Notably, maternal parity status was undocumented for two deliveries within the care conversion cohort. Furthermore, for 6.70% of the aggregate obstetric dataset ($n = 25$), localized tracking records regarding specific delivery pathways or final clinical endpoints were unavailable.

Cohort Parity	Analgesic Conversion Rate [%]
Primiparous ($n = 51$)	25.37%
Multiparous ($n = 16$)	9.52%

Table 16: Analgesic conversion rates to secondary care stratified by patient parity

The localized distribution of medicinal gas administration durations across the clinical cohort is illustrated in Figure 8, which explicitly contrasts the profile of the entire patient population against the sub-cohort that ultimately converted to secondary obstetric care. For the comprehensive dataset (top panel), the administration duration exhibits a highly pronounced right-skewed (positively skewed) distribution, characterized by a median usage time of 50.00 minutes relative to the calculated mean of 56.19 ± 45.16 minutes.

Conversely, a distinct clinical and operational shift emerges when isolating the patient subset whose care was escalated to secondary obstetrician-led management (bottom panel). Within this conversion subgroup, the minimum administration duration rises to 4.00 minutes, and the median duration shifts significantly upward to 72.00 minutes. Instead, this rightward shift implies a sustained clinical trial phase, demonstrating that first-line midwifery teams routinely utilize N_2O as an extended bridging strategy before progressive labor complications or escalating physiological pain demands necessitate a formal transfer of obstetric responsibility.

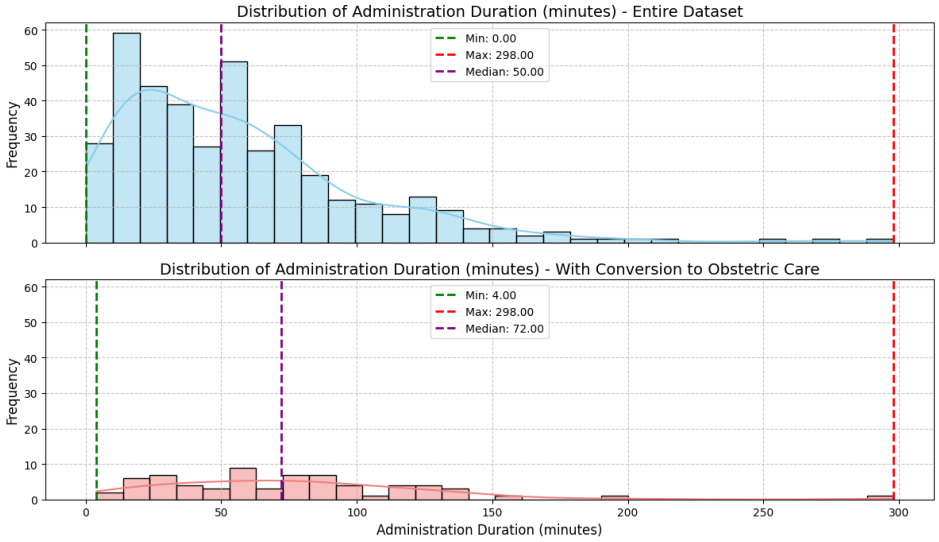

Figure 8: Distribution of duration of administration

The primary clinical indications necessitating an analgesic conversion to secondary care ($n = 69$) were evaluated to determine the underlying drivers of care escalation. Non-progressive labor (failure to progress during cervical dilation) constituted the most frequent indicator, accounting for 30.43% of cases ($n = 21$). Other or specific secondary medical indications represented 20.29% ($n = 14$), while undocumented or unknown rationales accounted for 18.84% ($n = 13$) of the conversion cohort.

Direct strategic adjustments, including deliberate transitions or temporary bridging to epidural analgesia (EDA) and direct shifts to remifentanil patient-controlled analgesia (PCA), each accounted for 13.04% of the care escalations ($n = 9$ each). Conversely, acute patient tolerance and therapeutic limitations were minor drivers; adverse clinical side effects, such as vasovagal episodes or syncope, accounted for 2.90% ($n = 2$), and documented insufficient primary analgesic efficacy accounted for 1.45% ($n = 1$) of the total conversions. These categorical distributions are compiled comprehensively in Table 17.

Indication for Care Conversion	**Count (n)**	**Proportion (%)**
Non-progressive labor (Failure to progress)	21	30.43%
Other / Specific secondary medical indication	14	20.29%
Unknown / Undocumented rationale	13	18.84%
Transition or temporary bridging to EDA	9	13.04%
Direct transition to Remifentanil PCA	9	13.04%
Adverse side effects (e.g., syncope/fainting)	2	2.90%
Insufficient analgesic efficacy	1	1.45%
Total	**69**	**100.00%**

Table 17: Granular distribution of clinical rationales dictating obstetric conversion to secondary analgesia ($n = 69$)

3.4.3 Projected Clinical and Logistical Consequences of Total Withdrawal

A total withdrawal of N_2O availability from the obstetrics department is projected to introduce significant clinical and logistical disruptions, primarily affecting patient institutional selection and intrapartum care tier routing. Qualitative data indicate that the availability of N_2O analgesia serves as a decisive factor for expectant mothers when selecting the LUMC as their preferred delivery facility. Consequently, a complete decommissioning of this service is anticipated to induce patient diversion, driving expectant mothers to seek care at alternative regional hospitals that maintain comprehensive, non-invasive pharmacological pain management options.

Logistically, the removal of this modality would precipitate an upstream escalation in secondary clinical care admissions. Within primary-care (midwife-led) obstetric frameworks, N_2O represents the sole permissible pharmacological analgesic intervention. Operationally, the administration of the gas mixture serves a vital buffering function, temporarily stabilizing patients and managing labor pain during periods of high capacity strain or peak workflow saturation within the secondary-care (obstetrician-led) labor wards.

However, the underlying data suggest that this primary-care intervention predominantly functions as a short-term bridging strategy rather than a terminal solution; because the progressive physiological demand for potent analgesia persists, the majority of these cases ultimately require an inevitable transfer of obstetric responsibility to secondary-care institutional personnel to facilitate regional blocks or systemic opioids. Decommissioning N_2O would eliminate this critical operational buffer, forcing earlier care escalations and compounding the existing bed-capacity and staffing constraints within the institution's secondary-care delivery infrastructure.

3.4.4 Comparative International Analysis: The United Kingdom Perspective

In contrast to the Netherlands, where planned home births are structurally normalized, the UK exhibits a significantly higher rate of institutional, hospital-based deliveries. Within UK obstetric frameworks, medicinal N_2O is administered with profound ubiquity; estimates indicate that approximately 76% of all hospital-based deliveries involve N_2O utilization. Structurally, UK acute maternity facilities are typically partitioned into midwife-led "birthing centres" (providing primary-care workflows) and obstetrician-led "labour wards" (providing secondary-care workflows). Notably, N_2O is standardly available as a baseline analgesic option across both operational environments.

The clinical parameters governing administration in the UK are also considerably broader than contemporary Dutch protocols. Rather than being restricted to specific windows of active labor, gas administration typically commences at 3–4 cm of cervical dilation and continuously extends through delivery until the completion of post-partum perineal suturing and related gynecological interventions. Consequently, cumulative patient exposure durations are significantly prolonged, routinely ranging between 4 and 18 hours. Within this temporal matrix, maternal parity operates as a key determinant of total consumption; multiparous patients routinely demonstrate accelerated labor progression, thereby requiring shorter cumulative exposure windows relative to primiparous cohorts.

Despite the widespread deployment of N_2O as a first-line intervention, the rate of conversion to secondary care is remarkably high, with approximately 63% of patients ultimately transitioning to regional epidural anesthesia or systemic opioids. Interestingly, the utilization of remifentanil PCA remains highly institution-specific and is, on a macro level, substantially less common in the UK than in the Netherlands, where remifentanil represents a mature and widely distributed alternative.

From a regulatory and clinical governance perspective, UK risk-mitigation frameworks diverge significantly from the stringent standards maintained at institutions like the LUMC. There is no statutory requirement for specialized certification or mandatory training before clinical personnel can administer the gas; in clinical practice, auxiliary or supportive healthcare staff frequently facilitate delivery alongside primary midwives. Furthermore, screening protocols for critical patient contraindications, such as pre-existing vitamin B_{12} deficiencies or a clinical history of substance abuse, are largely absent from routine pre-procedural workflows. Despite these differences in occupational and clinical exposure controls, the availability of the gas remains heavily mandated; guidelines issued by the National Institute for Health and Care Excellence (NICE) explicitly classify N_2O as an essential component of high-quality, accessible intrapartum care.

3.5 Discussion

3.5.1 Data Integrity, Administrative Decoupling, and Registry Limitations

A primary methodological challenge identified in this study is the reliance on manual paper records for quality control and billing verification within primary-care workflows, rather than direct integration into the institution's EHR system. Because patients undergoing first-line intrapartum care are managed by community midwifery clinics operating within the hospital's physical infrastructure, they are frequently not formally checked into the facility's centralized EHR at the onset of administration. While the completion of manual paper registries is legally mandated for insurance documentation, clinical auditing revealed a high rate of missing or incomplete data entries. This documentation gap significantly limited the longitudinal tracking of analgesic care escalations and restricted the sample size for corresponding pre- and post-treatment pain score evaluations, a phenomenon widely documented in retrospective evaluations of decentralized clinical workflows [129].

This administrative tracking gap directly compromised the evaluation of pain alleviation efficacy via the VAS. Although institutional protocols dictate that the VAS score must be recorded at initialization and systematically re-evaluated every 15 minutes alongside secondary vital signs, real-world monitoring compliance was highly variable and frequently omitted during active labor stages. Furthermore, the registry captured a distinct clinical pattern wherein maternal pain scores initially decreased but subsequently experienced a sharp rebound over prolonged utilization windows. This observation aligns with established pharmacological profiles demonstrating that the analgesic efficacy of inhaled N_2O peaks and plateaus within a 3-to-4-hour window, after which its therapeutic utility declines precipitously due to receptor tachyphylaxis or progressive labor intensity [119]. Consequently, the data suggest that extending gas delivery beyond this therapeutic ceiling yields diminishing clinical returns; if a patient reports insufficient pain relief during the initial phase of administration, prolonged usage rarely circumvents the ultimate necessity for alternative secondary care interventions.

These documentation discrepancies were further amplified when attempting to benchmark institutional findings against macro-level data from the national perinatal registry, PeriNed. A comparative analysis of PeriNed records from 2021 through 2025 revealed systemic underreporting and data gaps regarding the total volume of deliveries and direct N_2O utilization rates at the LUMC, particularly within the primary-care sector. The national database consistently recorded a lower annual volume of births and gas administrations than what was verified by internal institutional procurement logs and billing records. This data gap within the national registry precludes drawing definitive statistical conclusions regarding whether the LUMC exhibits an elevated or suppressed consumption baseline relative to regional or national averages. Furthermore, the care transfer categories utilized by PeriNed are structurally over-broad, aggregating all maternal transfers from the initial booking phase through postpartum care into generalized classifications. Because the tracking metrics within the national registry are subject to systemic categorization errors, the reported data regarding care escalations specifically driven by non-progressive labor or insufficient primary analgesia cannot be considered completely reliable for institutional benchmarking [130].

3.5.2 Occupational Health Compliance and the Engineering-Operational Paradox

To maintain rigorous compliance with statutory Dutch Working Conditions Act regulations (ARBO standards), the institution enforces an occupational exposure ceiling restricting clinical staff to a maximum of two N_2O administrations per shift. Crucially, the protocol safeguards staff autonomy by granting midwives the unilateral right to refuse gas initialization if they determine that environmental or patient-specific constraints compromise occupational health safety. To guarantee maternal and fetal safety under these guidelines, patient assessment is mandated at 15-minute intervals across four clinical parameters: oxygen saturation (SpO_2), VAS pain metrics, Ramsay Sedation Scale scores, and systemic blood pressure. However, the data collected in this study demonstrate that the real-world implementation of this multi-parameter monitoring matrix was highly inconsistent and poorly recorded by frontline staff, echoing broader literature highlighting compliance barriers in high-acuity obstetric environments [131].

This operational inconsistency is further complicated by a striking institutional paradox identified between the technical engineering standards and the clinical training frameworks implemented at the LUMC. Frontline primary-care midwives undergo a multi-modal certification curriculum twice a year, comprising an asynchronous e-learning module, a written theoretical examination, a technical cart assembly tutorial, and a practical bedside competency check, which is capped at four participants per session to ensure close oversight. However, an evaluation of this curriculum revealed that instructions regarding cylinder residual pressure are entirely omitted. In direct contrast to engineering specifications, which mandate that a minimum safety residual pressure must be preserved inside the cylinder to protect internal valves against atmospheric moisture contamination and structural damage [18], clinical training instructors explicitly direct staff to exhaust cylinders completely. Midwives are trained that a cylinder is spent when a physical vacuum effect occurs at the patient's face-mask interface. This discrepancy demonstrates a clear communication gap between the facility's technical maintenance infrastructure and its active clinical workforce.

3.5.3 Ergonomic Vulnerabilities and Environmental Infrastructure Constraints

The physical delivery and active capture of waste gas represent another notable source of clinical and mechanical friction. Institutional protocols strictly bar gas administration unless the secondary active vacuum-scavenging infrastructure is fully operational and correctly positioned. However, qualitative assessments from both patients and attending clinical staff identified the connection junction between the flexible suction hose and the double-mask structure as the primary mechanical failure point of the system, noting that the component frequently uncouples during active patient movement. Furthermore, both primary-care midwives and laboring patients routinely reported that the double-mask apparatus is structurally cumbersome and physically uncomfortable. This ergonomic drawback acts as a significant clinical barrier; if a laboring patient cannot comfortably tolerate the interface, they are frequently unable to achieve the psychological and physical relaxation required for successful labor progression, thereby rendering the pharmacological intervention ineffective.

Crucially, these structural vulnerabilities in waste-gas containment demonstrate why localized air monitoring protocols must be extended beyond active patient-care zones and into technical maintenance environments. Expanding surveillance to these peripheral engineering areas is essential to protect non-clinical facility staff from occupational exposure driven by building-wide distribution losses and chronic pipeline leakage.

In addition to ergonomic limitations at the patient interface, the physical architecture of the facility introduces significant technical variations in gas delivery. Because delivery suites are positioned at varying physical distances from the primary technical maintenance rooms housing the centralized extraction pumps, the overall length of the vacuum-scavenging pipeline network fluctuates considerably between rooms. These architectural variations induce localized pressure differentials within the extraction lines across different labor rooms. Consequently, the efficiency of the active waste-gas capture system is not uniform across the department, creating a localized variable that can directly influence ambient exposure levels for clinical staff and alter the delivery ergonomics at the bedside.

3.5.4 Efficacy Profiles, Parity Dynamics, and Analgesic Conversion Logic

Despite the technical and ergonomic limitations identified across delivery workflows, longitudinal registry tracking demonstrates that the macro frequency of deliveries involving N_2O remained exceptionally stable over the multi-year

observation window, showing no significant upward or downward trends. Strikingly, while the quantitative reduction in patient-reported VAS scores was statistically modest (1.63 ± 1.48 points), qualitative satisfaction metrics consistently achieved high baseline averages among both patients (7.31 ± 2.16) and clinical operators (7.76 ± 1.88).

This clear disparity between objective pain reduction and subjective qualitative assessment highlights a well-documented phenomenon in obstetric literature known as the nitrous oxide analgesic paradox [132]. Extensive clinical literature confirms that while N_2O possesses limited objective anesthetic potency and fails to alter physiological nociceptive scores as drastically as regional blocks, it exhibits powerful anxiolytic and sedative properties. The gas mixture fundamentally alters the affective perception of labor distress, transforming the patient's psychological relationship to pain by inducing mild dissociation and euphoria rather than total sensory block [121]. Furthermore, these elevated satisfaction parameters are strongly tied to the preservation of maternal autonomy; because the demand-valve configuration puts the timing, depth, and volume of gas inhalation entirely under the patient's control, it enhances psychological coping mechanisms and feelings of environmental command during active labor stages, explaining why patients and healthcare providers remain highly favorable towards this modality despite its limited objective analgesic capacity [133].

However, when stratified by parity, primiparous cohorts exhibited a significantly elevated care conversion rate of 25.37% compared to just 9.52% among multiparous patients. This divergence is clinically logical, as primiparous labors are characterized by prolonged cervical dilation trajectories, making them more likely to outlast the 3-to-4-hour efficacy ceiling of the gas and ultimately require secondary care interventions [24]. Crucially, a comparative analysis of the data distribution curves revealed no structural difference in the trend lines mapping administration durations between the total population and the conversion cohort (as visualized in Figure 8). The mathematical identity of these trends indicates that setting an arbitrary time limit or maximum duration cap on primary N_2O use before enforcing care escalation is entirely unsupported by clinical outcomes.

This distinct parity dynamic provides an empirical foundation for targeted clinical advice and risk-stratified labor routing. Because primiparous individuals experience significantly higher care escalation rates, first-line midwifery staff should actively manage clinical expectations and discourage over-reliance on N_2O when extended labor durations are anticipated. Specifically, if a primiparous patient requests pharmacological pain management during the early active phase of labor, and the attending midwife estimates that the remaining duration of delivery will exceed the proven 3-to-4-hour therapeutic window of the gas, N_2O should not be recommended as a primary solution. Instead, midwives should guide the patient toward early regional or systemic alternatives to prevent unnecessary maternal fatigue, reduce receptor tachyphylaxis, and optimize secondary-care workflow efficiency.

Additional clinical suggestions include reserving N_2O deployment strictly as a short-term bridging option for patients presenting in advanced active labor (≥ 7 cm cervical dilation) where the delivery window is predictably brief, or utilizing it exclusively to manage acute pain during post-partum perineal suturing and manual placental removals, where its rapid onset and clearance match the short clinical duration of the procedure. To optimize this clinical decision-making framework, midwives must understand the comparative efficacy profiles of N_2O relative to secondary-care pharmacological interventions shown in Table 18.

Analgesic Modality	**Objective Pain Alleviation Efficacy**	**Maternal Mobility Status**	**Primary Clinical & Logistical Risk Factors**
Nitrous Oxide (N_2O)	**Modest to Low:** Typically yields a minor 1-to-2 point reduction on standard VAS/NRS scales; relies heavily on anxiolysis [132].	**Fully Preserved:** Patient retains complete motor function and baseline ambulation capabilities.	Therapeutic ceiling limits efficacy to 3–4 hours; introduces occupational ambient exposure and high carbon costs [133].
Remifentanil PCA	**Moderate to High:** Provides profound systemic opioid-driven analgesia; significantly superior to N_2O in reducing absolute pain scores [134].	**Partially Maintained:** Minimally impacts motor control, though continuous intravenous tethering restricts free ambulation.	Requires active continuous maternal pulse oximetry monitoring due to risks of respiratory depression [135].
Epidural Analgesia (EDA)	**Superior (Gold Standard):** Completely blocks nociceptive pathways, offering near-total pain eradication unmatched by any primary method [47].	**Severely Restricted:** Induces localized sympathetic and motor blocks, typically confining the patient to bed-rest workflows.	Demands an immediate transfer of care; associated with maternal hypotension and instrumental delivery risks [47].

Table 18: Comparative clinical performance, mobility, and safety profiles of intrapartum analgesic modalities

When Care escalation occurred, it was consistently driven by four primary clinical rationales: non-progressive labor (cervical dilation arrest), specific high-risk medical indications, undocumented paper files, or a direct strategic transition to epidural analgesia (EDA) or remifentanil PCA. In cases complicated by non-progressive labor, standard clinical intervention dictates the initiation of synthetic oxytocin augmentation, which routinely necessitates secondary

regional blocks for adequate pain management [47]. In acute or urgent secondary medical situations, clinical priority shifts immediately to rapid fetal delivery, meaning that secondary administrative logging on paper charts is frequently omitted or forgotten during the emergency. In all such care escalation scenarios, obstetric responsibility is fully transferred to the institution's second-line medical staff.

3.5.5 Strategic Recommendations and the Capital Infrastructure Investment Dilemma

From an operational perspective, qualitative registry tracking confirms that the availability of N_2O serves as an important driver for institutional selection; expectant mothers actively request admission to the LUMC specifically to retain access to this non-invasive pharmacological option. Decommissioning this service would result in patient diversion to competing regional facilities. However, because the absolute departmental utilization frequency is low, the quantitative data gathered in this study do not provide a strong economic justification for heavy capital investments in a dedicated, large-scale catalytic cracking plant for the maternity ward alone.

This creates a complex capital dilemma, as the raw global warming potential of unmitigated gas venting remains high. To balance these competing environmental and economic variables, three distinct structural strategies should be evaluated:

Option 1: Cross-Departmental Sharing of Mobile Cracking Units
The first approach involves deploying or sharing the mobile catalytic cracking infrastructure currently utilized within the adjacent pediatric surgery unit. However, this strategy introduces severe operational friction; mobile cracking units require a mandatory 30-minute pre-heating latency to reach optimal catalyst decomposition temperatures [136]. This engineering delay directly conflicts with the clinical reality of acute obstetric pain management, where patients require immediate analgesic initialization. Implementing this model would necessitate an extensive overhaul of intrapartum workflows and require the immediate re-certification of all active midwifery staff.

Option 2: Centralized Scavenging Integration
The second alternative involves integrating a centralized catalytic cracking network directly into the general centralized scavenging line. This approach would successfully capture waste gas without introducing bedside workflow delays. However, before authorizing this capital expenditure, further research must be conducted to determine the exact concentration profile of the waste gas inside the extraction lines relative to general HVAC air dilution, as high baseline dilution can severely degrade the chemical efficiency of catalytic destruction beds [104].

Option 3: Modular Scavenging Links
The third option entails retrofitting modular, small-scale mobile cracking components directly into the centralized vacuum lines, offering a lower capital entry point. Similar to the centralized model, this configuration requires precise baseline validation data tracking the true gas volume entering the scavenging lines versus the volume lost to ambient room ventilation before mechanical deployment can be authorized.

Should the institution pursue the highest tier of the circular economy "R-ladder" framework (Refuse) and fully decommission N_2O, primary midwives would require an alternative pharmacological option to offer their patients. While remifentanil PCA is available within the LUMC and preserves advantages such as complete maternal ambulation and full pelvic sensation (unlike epidurals) its administration demands continuous monitoring and clinical oversight that falls outside the standard scope of first-line midwifery practice. Non-opioid pharmacological alternatives suited to a primary care setting therefore remain an important yet underexplored avenue. Identifying such options would be essential to managing the operational impact on secondary care capacity while supporting a permanent reduction in the institution's direct greenhouse gas emissions.

When benchmarked against international frameworks, such as the United Kingdom's obstetric landscape, the Dutch healthcare model demonstrates superior structural maturity regarding direct source reduction. In the UK, the structural lack of mandatory staff certifications, the widespread reliance on continuous-flow masks over demand valves, and continuous usage protocols extending up to 18 hours across both birthing centers and labor wards result in highly elevated environmental emissions and increased ambient exposure risks for clinical personnel.

This tension is further complicated by a profound institutional and regulatory paradox currently unfolding within the UK healthcare system. On one side, the National Health Service (NHS) is intensely focused on reducing direct carbon outputs under its "Greener NHS" initiative, actively mandating a reduction in volatile anesthetic gas waste and the optimization of pipeline infrastructure to curb direct emissions and lower operational expenditures [137]. On the other side, clinical governance frameworks issued by the National Institute for Health and Care Excellence (NICE) explicitly mandate that nitrous oxide must be maintained as a baseline, universally accessible analgesic option to guarantee high-quality, non-invasive intrapartum care standards [128]. This creates an operational gridlock where sustainability initiatives actively discourage medical gas deployment while clinical quality guidelines legally mandate its integration into the obstetric workflow.

This cross-border contrast underscores the profound impact of national legislative architectures in driving or suppressing direct healthcare emissions, proving that the localized strategies engineered within the Netherlands serve as an instructive template for international healthcare systems seeking to de-carbonize their clinical operations without compromising the safety or autonomy of primary care delivery.

General Discussion

The empirical and qualitative findings established across this study highlight a highly complex, multi-layered socio-technical ecosystem where regulatory frameworks, building architecture, economic constraints, and clinical traditions converge to govern the utilization and mitigation of medicinal N_2O.

Chapter 1 established the macroeconomic and structural baseline, identifying a stark geopolitical stratification between the Global North and South, driven by the material intensity and capital entry barriers of modern containment systems [54, 55].

Chapter 2 contextualized these challenges within a major academic medical center (LUMC), exposing a wide operational divergence between absolute institutional procurement registries and localized, real-world carbon footprints heavily influenced by point-of-use destruction technologies [104].

Finally, Chapter 3 executed a clinical deep-dive into obstetric care workflows, revealing the "nitrous oxide analgesic paradox", wherein high qualitative maternal satisfaction and psychological anxiolysis decouple from statistically modest objective pain mitigation scores [132, 133].

When synthesized, these findings reveal that a sustainable transition to low-carbon anesthesia cannot be achieved through siloed environmental directives or end-of-pipe technology replacements alone. Instead, it mandates a comprehensive institutional strategy that reconciles technical engineering realities with real-world clinical behavior and digital administrative registries.

Strategic Advice and Actionable Guidelines for Hospitals

To bridge the persistent gaps identified between policy and clinical practice, healthcare institutions must implement structural interventions across three core operational dimensions.

Infrastructural and Engineering Asset Allocation

Decommissioning of Centralized Manifold Piping Networks

Legacy centralized N_2O piping infrastructure represents one of the most significant sources of institutional greenhouse gas waste in hospital settings. Chronic degradation at copper sub-structural joints, terminal wall valves, and manifold distribution lines can account for fugitive atmospheric losses of 80%–95% of total N_2O procurement before the gas reaches the point of care [57]. Given that N_2O carries a 100-year (GWP_{100}) of 273 relative to CO_2 [9], these systemic infrastructure losses constitute a disproportionate and largely preventable environmental liability.

In the Netherlands, transitioning away from centralized piping networks is driven by convergent clinical, occupational, and sustainability frameworks. At the clinical level, the *NVA Leidraad Perioperatieve Zorg* (2024) mandates that anaesthesia departments establish protocols prioritizing Total Intravenous Anaesthesia (TIVA) and minimizing N_2O use [67]. Because centralized piped-gas infrastructure represents a permanent, institution-wide commitment to gas delivery, its operation is structurally incompatible with this directive. Furthermore, the *Milieu Platform Zorg* (MPZ) operationalizes this compliance as an auditable criterion within its environmental performance standards [68].

At the occupational health level, the *Arbocatalogus Inhalatieanesthetica*, established under the Dutch *Arbeidsomstandighedenwet*, sets an 8-hour time-weighted average (TWA) limit for N_2O at 152 mg/m^3, with an ALARA target of 38 mg/m^3 below which repeat monitoring is not required [63]. Driven by updated toxicological evidence, university medical centres (UMCs) and NVZ-affiliated hospitals implemented a more stringent exposure limit on 1 January 2026 [138]. Due to structural leakage, centralized piping systems are difficult to maintain within these tightening thresholds in clinical areas with prolonged staff exposure. Conversely, cylinder-based point-of-care delivery completely eliminates the building-scale network, removing the primary source of chronic background exposure.

At the sustainability level, the *Green Deal Duurzame Zorg 3.0* (GDDZ 3.0), a 2023–2026 covenant between the Dutch government and over 550 healthcare organizations, commits signatories to a 55% reduction in direct -equivalent emissions by 2030 and full climate neutrality by 2050, explicitly targeting medicinal gases [66]. Because N_2O pipeline leaks constitute direct Scope 1 emissions under this framework, eliminating these distribution losses via decentralization directly advances GDDZ 3.0 compliance.

Taken together, these frameworks create a mutually reinforcing regulatory environment in which the decentralized cylinder model has become the operationally and legally preferred standard. Point-of-care, cylinder-based delivery coupled to single-patient demand-valve configurations eliminates building-scale upstream distribution losses, materially simplifies institutional carbon accounting, and enables compliance with the concurrent occupational exposure, clinical quality, and sustainability requirements imposed by Dutch law and professional standards [57, 67, 66].

Workflow-Specific Tailoring of Abatement Technologies

Institutions should reject uniform, facility-wide procurement templates and instead match downstream gas mitigation hardware strictly to departmental workflow characteristics:

- **Acute and High-Throughput Environments (e.g., Emergency Departments, Obstetrics):** These clinical pathways are inherently unpredictable and time-critical. Because mobile catalytic cracking units require a mandatory 30-minute thermal pre-heating phase to reach catalyst activation temperatures, they introduce

severe operational delays at the bedside [136]. Acute zones must therefore be structurally integrated directly into centralized vacuum-scavenging networks (AGSS) connected to a continuously active, facility-scale destruction node to ensure an immediate, plug-and-play user interface.

- **Scheduled and Elective Environments (e.g., Pediatric Outpatient Clinics, Planned Dentistry):** These departments operate within organized, block-scheduled frameworks. Here, mobile catalytic cracking units represent an ideal, low-barrier capital investment. Pre-heating latencies can be systematically absorbed into standard pre-procedural room preparation protocols, successfully decomposing up to 99% of processed waste gas into inert N_2 and O_2 molecules without disrupting active workflows [104].

Clinical Practice Reforms and Labor Routing Optimization

Risk-Stratified Obstetric Labor Routing

Due to the high care conversion rate of 25.37% among primiparous patients (compared to just 9.52% in multiparous individuals), clinical protocols must explicitly discourage the initiation of inhaled N_2O during the early active phase of labor. Because first-time labors feature inherently prolonged cervical dilation trajectories, these patients almost universally require analgesic support that far outlasts the strict 3-to-4-hour therapeutic ceiling of nitrous oxide. Introducing N_2O prematurely guarantees that its clinical efficacy will be exhausted long before delivery, leaving patients vulnerable to receptor tachyphylaxis and severe maternal fatigue during the most intense stages of labor [119, 24].

Consequently, first-line midwifery staff must actively restrict early N_2O administration for primiparous patients and anyone in early labor. Instead of relying on short-term options early on, clinical teams should proactively guide these patients toward early regional or systemic alternatives, such as Remifentanil PCA or Epidural Analgesia (EDA), to sustainably preserve maternal energy and optimize secondary care workflow capacity (Table 19). Inhaled N_2O should be strictly rationed as a short-term bridging tool reserved exclusively for advanced active stages ($\geq$ 7 cm cervical dilation) or acute post-partum interventions like perineal suturing and manual placental removals.

Analgesic Modality	Objective Alleviation Efficacy	Maternal Mobility Status	Primary Clinical & Logistical Risks
Nitrous Oxide (N_2O)	**Modest to Low:** Yields minor 1–2 point VAS reduction; relies heavily on anxiolysis [132].	**Fully Preserved:** Receptors preserve complete motor function and ambulation.	3–4 hour therapeutic ceiling; ambient occupational exposure risks [133].
Remifentanil PCA	**Moderate to High:** Profound systemic opioid analgesia; superior to N_2O in absolute scores [134].	**Partially Maintained:** Intravenous tethering limits free ambulation; motor control preserved.	Mandates continuous pulse oximetry due to transient maternal respiratory depression [135].
Epidural (EDA)	**Superior (Gold Standard):** Complete sensory block of localized nociceptive pathways [47].	*Severely Restricted:* Induces sympathetic blocks, confining patient to bed-rest.	Direct care transfer required; risks of maternal hypotension and instrumental delivery [47].

Table 19: Comparative performance, mobility, and risk profiles of intrapartum analgesic modalities

Governance, Communication, and Fiscal Auditing

Aligning Technical and Clinical Training Gaps

Hospitals face a sharp conflict between engineering standards and clinical practice. While technical specifications require maintaining residual pressure inside gas cylinders to prevent valve degradation and moisture contamination [18], clinical educators often instruct staff to exhaust them completely. Because distributors vent this remaining gas into the atmosphere before refilling, counting the full volume as an emission remains accurate for institutional carbon accounting; however, completely exhausting the cylinders accelerates hardware wear. To resolve this, clinical certification pathways must integrate industrial gas safety education, bridging the communication gap between technical maintenance teams and the frontline clinical workforce.

Structured Representation and Pre-Implementation Auditing

Strategic environmental committees (such as hospital anesthetic gases boards) are frequently decoupled from practical bedside expertise, completely omitting primary-care providers who actively administer the gas (e.g., community midwives or emergency nurses) from their rosters. Institutions must formally restructure these governance frameworks to mandate clinical end-user representation.

Furthermore, before authorizing new equipment lines, management must enforce a multi-tiered pre-implementation audit. This pathway must balance low-barrier initial procurement costs against compounding, hidden operational

expenses (OPEX driven by single-use consumables and rigid technician calibration intervals), while contrasting standard atmospheric displacement layouts against the lifecycle carbon efficiency and localized ergonomics of active catalytic destruction architectures [74, 75, 76].

Forward-Looking Multidisciplinary Research Agenda

To drive the next generation of healthcare de-carbonization and support empirical, evidence-based administrative asset allocation, future scientific and clinical research should prioritize the following five trajectories:

Empirical Quantification of HVAC Dilution vs. Source-Capture Kinetics

While clinical rooms are increasingly outfitted with source-capture scavenging loops or active cracking interfaces, a critical compliance gap remains unresolved: the precise ratio of escaped waste gas evacuated through source-capture scavenging versus the volume diluted and drawn into general HVAC ventilation lines is currently unmonitored.

Future engineering and industrial hygiene studies must deploy real-time ambient air-monitoring sensor networks across both active patient-care zones and technical maintenance environments (e.g., manifold spaces and technical exhaust hubs). This empirical validation is essential to definitively verify compliance with statutory occupational exposure limits (OEL), such as the Dutch Working Conditions Act (*Arbowet*) limit of 152 mg/m^3 (80 ppm), and to eliminate tracking deficits within institutional carbon accounting frameworks [109, 111].

Emission Assessments of Alternative Cryo-Systems

In specific interventional settings, such as cryoanalgesia applications during pediatric pectus excavatum repairs, N_2O is utilized purely for its mechanical and rapid physical cooling properties rather than its pharmacodynamic sedative profile.

While CO_2 is already utilized as an alternative cryogen and is expected to result in significantly lower emissions than nitrous oxide, a comprehensive, cradle-to-grave LCA may not be strictly necessary. Instead, immediate comparative research should focus on quantifying the exact volume of CO_2 versus N_2O consumed per patient. Furthermore, a critical bottleneck exists at the manufacturing level; medical device manufacturers must actively commit to developing and optimizing systems for CO_2 as a cryogenic gas, as current commercial setups, such as those currently utilized at the LUMC, do not yet support this capability. Accelerating this shift will require both targeted industrial innovation and active cross-institutional knowledge sharing.

Downstream Circular Infrastructure for Adsorption-Based Storage

Physical carbon-capture paradigms, such as point-of-use adsorption systems utilizing activated carbon or molecular sieves, demonstrate high efficiency in trapping volatile halogenated anaesthetic agents, including sevoflurane, isoflurane, and desflurane. The efficacy of activated carbon for these agents is attributable to their favourable physicochemical properties: large molecular size, significant polarity conferred by halogen substituents, and relatively high boiling points, all of which promote strong Van der Waals interactions with the carbon surface [33]. Systems such as CONTRAfluran (ZeoSys, Germany) operationalise this principle at the point of care, enabling passive adsorption of halogenated agents directly at the anaesthesia machine with subsequent off-site solvent recovery [139].

N_2O, however, is fundamentally incompatible with activated carbon adsorption. Its small molecular size (44 g/mol), negligible polarity, and very low boiling point ($-88\,^{\circ}C$) result in weak Van der Waals interactions, causing the molecule to pass through the adsorbent without meaningful retention [33]. In the clinical context, this physicochemical limitation is further compounded by the high moisture content of exhaled breath: water molecules competitively occupy adsorption sites, reducing the already insufficient uptake of N_2O [34]. Consequently, alternative recapture strategies, such as cryogenic condensation or direct recompression, are required for N_2O recovery, none of which are currently viable at the point of care.

Despite the promising performance of adsorption-based systems for halogenated agents, the commercial medical market currently lacks localised downstream processing networks capable of purifying and recycling the captured gas back into the medical supply chain at scale. Future research in industrial design and chemical engineering must investigate the recycling loop logistics, regulatory validation protocols, and purification parameters required to operationalise an integrated circular medical gas supply network encompassing both halogenated anaesthetic agents and N_2O.

Digital Integration and EHR Algorithmic Registry Design

The systematic reliance on manual paper logs for medical gas billing and quality control within decentralized primary-care workflows induces profound documentation gaps and administrative decoupling. These tracking errors cause significant data deficits in regional health audits and underreporting within national perinatal registries such as PeriNed [129, 130].

Medical informatics research should focus on developing automated EHR charting interfaces that dynamically track patient-specific utilization metrics (e.g., exact exposure durations, real-time demand-valve flow rates, and

cylinder mass differentiation). Research must evaluate if automated data streams optimize clinical audits and enhance real-world compliance with mandated vital-sign monitoring protocols [131].

Catalytic Destruction Kinetics Under Low-Concentration Streams

Before a healthcare facility authorizes substantial capital expenditures (CAPEX) to install centralized catalytic destruction frameworks within general building extraction networks, the chemical performance of the catalyst cores must be verified under high-dilution conditions. High-volume general building ventilation can severely dilute the concentration profile of waste medical gases before they reach a technical facility.

Rigorous fluid dynamics and chemical engineering research are required to determine the exact thermal degradation efficiency thresholds of catalytic beds processing heavily diluted ambient air matrixes, providing an empirical baseline for building-scale mitigation networks [104].

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