BRAINE - Big data Processing and Artificial Intelligence at the Network Edge

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Abstract	This technical report delivers detailed information about the development of a healthcare platform designed to integrate and utilise the features available on the BRAINE platform to improve the healthcare of patients using advanced techniques such as Artificial Intelligent and Digital Twins.
Keywords	Edge computing, Healthcare, AI, Digital Twin

Copyright

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List of abbreviations and Acronyms

Abbreviation	Meaning
AI	Artificial Intelligence
API	Application Programming Interface
CPU	Central Processing Unit
EEG	Electroencephalogram
EMDC	Edge Mobile Data Center
EU	European Union
GDPR	General Data Protection Regulation
GPU	Graphics Processing Unit
IoT	Internet of Things
IT	Information Technology
KPI	Key Performance Indicator
PoC	Proof of Concept
QSD	Qualified Synthetic Data
TBC	To Be Confirmed
TBD	To Be Defined

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1. Executive summary

BRAINE project along to Use Case 1 addresses the challenges in traditional cloud-based healthcare data processing, such as high data transfer costs, and security issues in sensitive healthcare environment along to the GDPR compliance, by implementing localized data processing through Edge Micro Data Centre (EMDC). Such synergy of the technologies could minimize the need for extensive data transfer to distant data centres and supports a customized environment for healthcare-specific applications.

One of the objectives of the Use Case 1 in the BRAINE project was to validate the concept of EMDC that provides edge computing technology on top of which patients' digital twins run. Use Case 1 (UC1) with focus on the deployment of a Patient Digital Twin system on the EMDC within a hospital ward environment, explores how the recent developments in the Medical Internet of Things could be applied in patient monitoring and healthcare analytics.

Currently healthcare service goes through the shift putting "patient at the centre of care", where focus is on tailoring healthcare delivery to the specific needs, preferences, and values of individual patients, rather than applying a one-size-fits-all approach. The driving force behind Use Case 1 with the EMDC is to support such shift in healthcare, bringing new technologies to the hospital's environment and to turn the hospital into a smart, high-tech place. Such development could help in mitigating logistical complexities, particularly critical in space and power-sensitive hospital environments.

EMDC offers efficient, real-time data processing in healthcare settings, while handling diverse and continuous patients' data streams. EMDC could replace conventional servers, addressing concerns around power usage, spatial constraints, and environmental impact. The innovative strategy is also in integrating hardware with the novel application aimed for the healthcare delivery services.

UC1's objective encompasses leveraging EMDC for advanced patient care, covering the entire spectrum of data acquisition from IoT devices, real-time analytics, data protection, and the integration of patient digital twin technology. This initiative involves the development of specialized components for data analysis, secure data handling supplemented by hardware and software optimization for enhanced computational power.

In summary, UC1 aims to provide a scalable, secure, and efficient edge-enabled healthcare platform, focusing on real-time patient monitoring through continuing calculation of major biomarkers and health status change by the patient digital twins. With such approach 'EMDC +_Patient Digital Twins' we could make hospitals not just more effective in terms of infrastructure utilization but also ensure data protection, privacy, and patient care. UC1 demonstrates the significant advantages that EMDC can offer in transforming healthcare technology, leading to better patient outcomes, personalized care, and predictive health analytics.

The EDMC technology running many patients' digital twins in real time was proved to be viable for hospital use, but it has not yet been tested in a clinical trial setting within the actual hospital. Further developments and projects in this area could support full exploration and realisation of such potential in clinical applications.

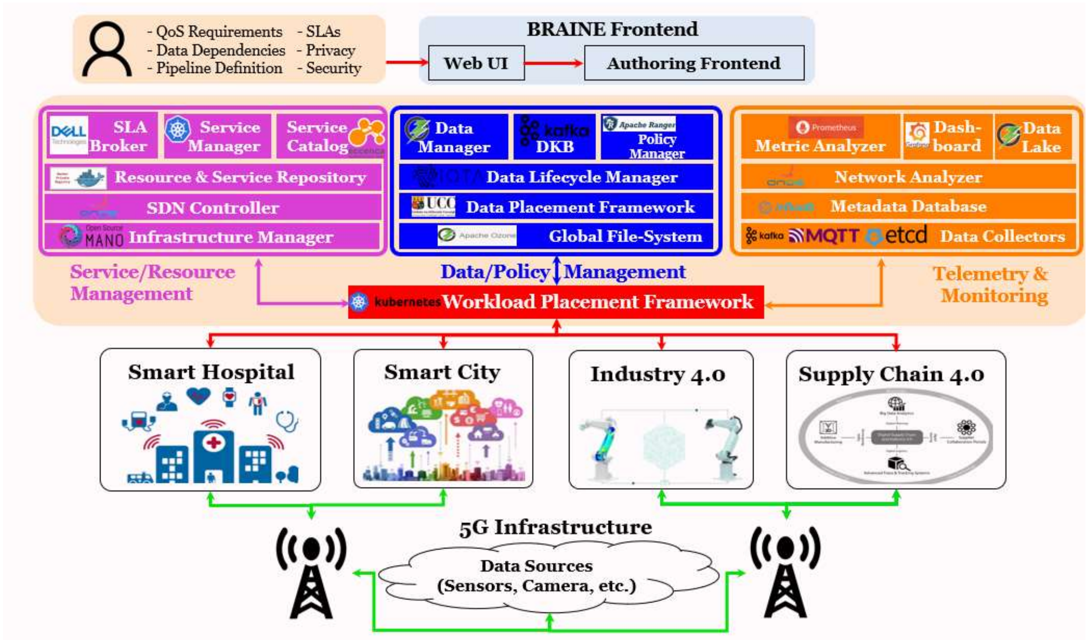


Figure 1 BRAINE Architecture

2. Use case overview

2.1. Background

75% of healthcare is funded out of public sources, and spending is continuously rising (OECD data on the EU Health expenditure, from 2005 to 2017) and specifically hospital spending. Furthermore, challenges to the European health system arise from the increasing life span of the population and a shortage of qualified labour force, particularly in healthcare. These issues need to be addressed as soon as possible.

Empowered patients, active caretakers and healthcare professionals have high expectations of the modern healthcare ecosystem. The healthcare centres are about to change from only a centralised medical entity with more decentralised capabilities supported by Bigdata, Artificial Intelligence and IoT offering treatments and nursing outside the hospital in small hubs (assisted healthcare centres, the concentration of assisted care homes) and patients living environment.

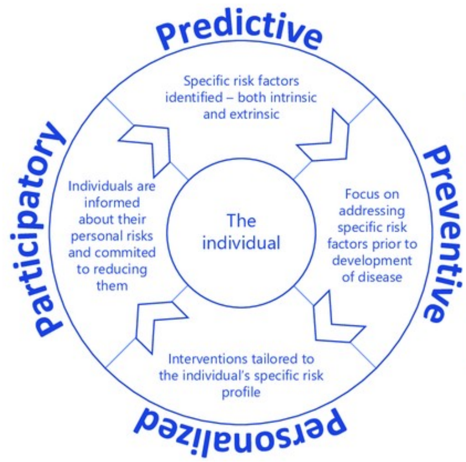


Figure 2.1 Patient centred healthcare [1]

IoT-based healthcare network architectures and platforms can address electively healthcare at different levels: paediatric and elderly care, chronic disease supervision, private health and fitness management. The decentralised [1]healthcare system and the Internet of Medical Things face technological challenges varying from near real-time responsiveness, big data sharing and security issues on data of medical and nursing structures, hospitals, caregivers, drugs and treatments effectiveness, patient-centred care, etc.

The proliferation of intelligent IoT devices with a shift towards edge computing allows most IoT data generated at the hospitals to be processed at the edge instead of the traditional centralised cloud data centre. This close-to-source data processing enables the facilitation of real-time applications such as those proposed by UC1, reduces data transmission, and lowers communication bandwidth; additionally, it enhances security, privacy, data protection, and energy efficiency.

BRAINE project with the Health UC1 application provides innovations that are aimed at radically enhancing patient care, boosting operational productivity, and remaining relevant in the changing healthcare domain.

[1] Visual representation of P4 Medicine: predictive, preventive, personalized, and participatory (and iterative) by Doherty, Timothy & Pasquale, Alberta & Michel, jean-pierre & Del Giudice, Giuseppe. (2019). Precision Medicine and Vaccination of Older Adults: From Reactive to Proactive (A Mini-Review). Gerontology. 66. 1-11. 10.1159/000503141.

2.2. Motivation

In the evolving field of electronic medical technology, such as the Internet of Medical Things technology in the healthcare domain, the integration of EMDC and Health Use Case presents a promising approach to **P4 Healthcare**: **P**redictive, **P**reventive, **P**ersonalised and **P**articipatory.

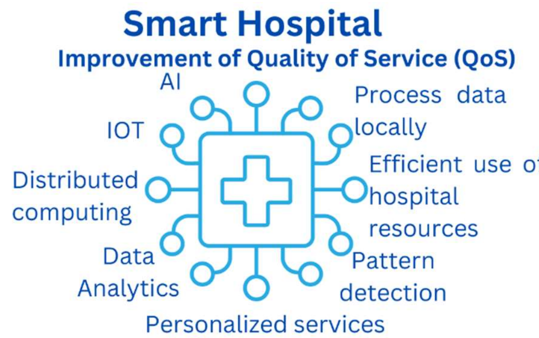


Figure 3 Smart Hospital service components

BRAINE EMDC innovative solution leverages the power of edge computing and patients' digital twins to transform how healthcare professionals and formal and informal caregivers can monitor, track, predict, and respond to health issues at the sources of healthcare data generation. In both hospitals and, for example, in nursing facilities, the crucial task of monitoring patient's vital signs still presents a complex challenge. Such as temperature, pulse rate, blood pressure, and respiratory rate, are essential for the timely detection of a patient's health deterioration. However, issues such as staff shortages, budgetary constraints, outdated data storage methods and lack of affordable innovation impede such effective monitoring. Studies show that neglecting timely changes in vital signs could lead to severe consequences, including fatalities. This issue is particularly acute during night-time observations when protocol adherence significantly drops.

There are protocols for monitoring vital signs, and they vary from country to country. Particularly, implementing early warning score (EWS) algorithms, like the UK's National EWS, provides a data-driven approach to patient care. However, even these can fail if not adhered to strictly. In acute cases such as sepsis and acute respiratory failure e.g., COVID-19, both significant contributors to in-hospital and nursing facilities deaths — delays in intervention can be lethal. Therefore, the ability of healthcare staff, particularly nurses, to recognise patterns and changes in patients' condition is invaluable.

In Health Use Case BRAINE EMDC, we apply the latest new methods and technologies to study and develop an approach of AI-driven medical-assisted caring to such facilities where a high density of critical patients' data is being generated by sensors, wearable devices, video cameras, and optional medical and health support equipment, collected and processed on-premises in real-time.

In the unique BRAIN approach to the implementation of Health UC1 we explored the possibility of realizing a personal AI-Digital Twin for each patient under treatment e.g., in the hospital ward. Each such digital health twin is running a generic bio-physical cyber model of the complex system "Human patient in a Living environment" which collects data from the personal IoT related to the individual (wearable bracelets and smartwatches, air quality sensors, beacons, medical diagnostic equipment, mobiles, etc.) and transform it into relevant monitoring and analytics services assisting the healthcare professionals, medical supervisors, and relatives of the patients.

With the EMDC BRAINE and Health UC this approach presents a transformative opportunity for hospitals. Such combination can significantly improve patient care by automatically collecting vital signs from each patient and integrate it with the data from different sources. When paired with machine learning techniques, this approach could provide valuable insights into patient health status and allow for proactive measures to be taken in the right time thus significantly enhancing the responsiveness, efficiency, and accuracy of medical care. Such setup could not only improve patient care but also optimize hospital operations by reducing the load on central data systems and streamlining data management. As a result, hospitals can achieve a higher level of efficiency and effectiveness in patient treatment and resource utilization, ultimately contributing to better healthcare outcomes and patient satisfaction.

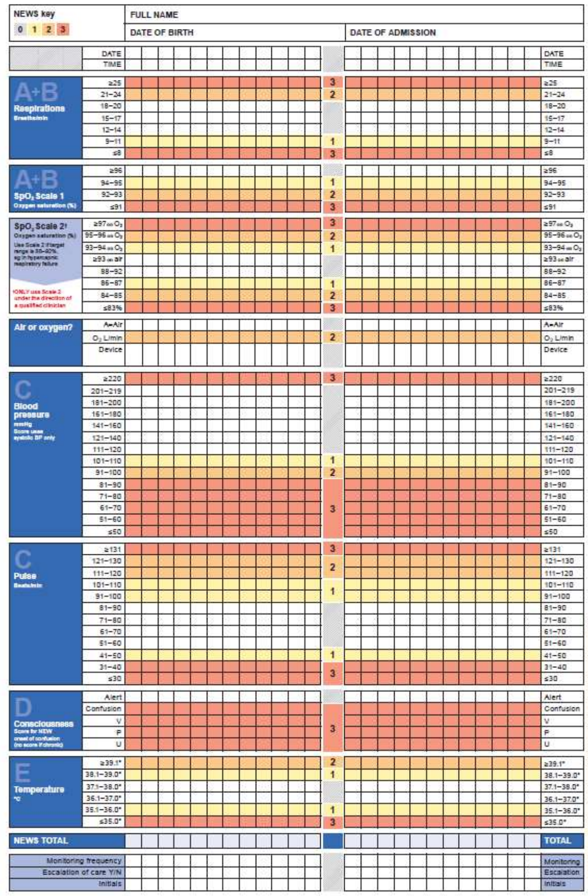


Figure 4 Chart representing National Early Warning Score, UK

In addition to enhancing patient care and hospital efficiency, BEAINE EMDC located on hospital premises, addresses another critical aspect of healthcare technology: the handling of highly sensitive health data. A local processing aligns with stringent data privacy regulations, ensuring that patient data is managed securely and in compliance with legal requirements.

Despite these significant advancements, the technology is currently at the TRL 4, proving the concept at a stage where its basic components have been validated but it is not yet widely adopted. However, such level signifies a crucial phase where the fundamental concepts of BRAINE EMDC in combination with patients' digital twin models have been proven to work in controlled settings. This early stage of development is particularly appropriate for such combination of technologies considering the innovative nature of integrating digital twins with edge computing in healthcare. While the concepts have shown promise during validation cycles, they are not yet mature enough for deployment in real-world hospital environments, which would be the next stage of development (TRL 5-6).

2.3. Objective

The healthcare industry is currently at a crossroads, with more and more data being produced, while the value of these data is not being realised, as providers are not able to use its potential in meaningful and relevant ways. BRAINE EMDC solution provides technology for the healthcare industry and enables of the maximisation of the value of healthcare data assets. The following table presents an overview of the key motivations behind the development of our activities during the BRAINE project, highlighting the potential benefits and transformative impact this combination can have on patient care and health outcomes.

Table 1 The UC1 Objectives and their description

Objective	**Description**
Implement Real-Time Data Processing at the hospital premises	This will enable immediate access to critical patient data, allowing faster and more accurate decision-making and relevant health support actions.
Develop Digital Health Twins for Patients	Digital Health Twins for patients enable personalised healthcare (P4), leading to more accurate diagnoses and effective treatment plans.
Reduced Latency	Edge computing reduces the time it takes for data to travel, leading to faster insights and responses.
Personalised Healthcare	A Health UC provides personalised health insights based on the individual's data that is collected instantly and continuously during the patient stay in the hospital ward. This can lead to more effective and tailored healthcare solutions.
Predictive Analysis	With continuous data collection and machine learning, the system can predict potential health deterioration and prompt relevant mitigation actions.
Data Privacy	Processing data at the edge can enhance data privacy and security.
Scalability	EMDC can be scaled up or down depending on the data processing needs. This makes the system flexible and cost-effective.
Improved Patient Outcomes	Ultimately, the main motivation is to improve patient outcomes.

2.4. Goals (KPI's)

The experimental assessment and validation of the overall EMDC BRAINE solution was performed during the validation phase of the project with the results presentation further in the document.

Specific KPIs:

Table 2 Specific KPI

Specific KPIs:	Results
KPI: Time required by a medical specialist to add a new biomarker or indicator to bio-physical model < 15 min	Achieved
KPI: Time required by a medical specialist to add new data source to patients’ digital twin system < 10 min	Achieved
KPI: Number of Man/Hours required for integration of hardware and software components in typical patients’ digital twin system for efficient operation in embedded edge applications < 16 hours	Achieved

3. Implementation and Integration

The use case implementation involved the deployment of the BRAINE EMDC integrated with new digital twin technology. The primary objective was to facilitate real-time data processing and analysis at the source of data generation, specifically patient data. This implementation encompassed the collection of data from various medical devices and sensors, with the EMDC responsible for immediate data processing.

Simplified model of patient digital health twins was created and then multiple model instances for patients at post-operational ward were run at BRAINE EMDC, serving as virtual counterparts for continuous health monitoring of each patient individually. These twins were updated in real-time, leveraging the processed data from the EMDC. The application of AI algorithms within the EMDC was a critical component, enabling the analysis of incoming data streams for health trend identification and potential emergency detection.

The technical architecture of the system ensured that the patients digital health twins functioned as effective tools for healthcare professionals in their decision-making processes. This use case was designed to test the feasibility of localized data processing in a healthcare environment, with a focus on improving response times, treatment personalization, and outcome efficiency.

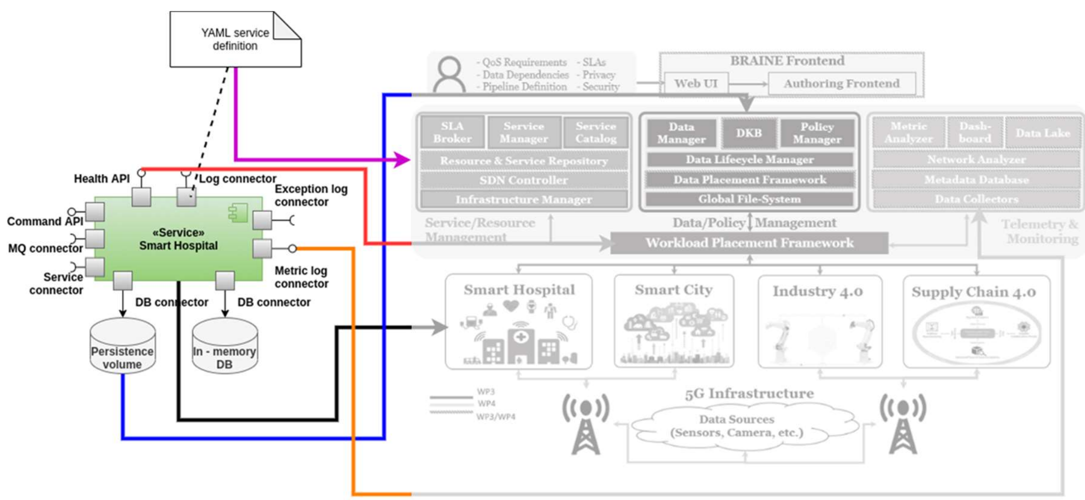


Figure 5 Graphical representation of patient Digital Twin system integration with EMDC

3.1. Use case implementation

The Use Case 1 implementation and validation includes specific steps as follows:

Performance Assessment: To perform a validation of BRAINE EMDC through the patients' digital health twin system's performance while the models are operating on the BRAINE EMDC hardware. Such validation involves measuring various performance metrics to determine how well the digital health twin models for multiple patients run within the given hardware constraints.

Patients Digital Health Twin Deployment: To deploy the maximum feasible number of Patients Digital Health Twins within the constraints of the current experimental hardware. The deployment aimed to test the scalability of the digital twin system and identify any limitations imposed by the BRAINE EDMC hardware capabilities.

Monitoring System Implementation: To set up a comprehensive monitoring system that is capable of tracking the performance and health of the Digital Health Twin models in real-time on BRAINE EMDC. This system should provide insights into system stability, resource utilization, and potential bottlenecks.

Hardware Impact Analysis: To evaluate the influence of the BRAINE EMDC hardware configuration on the operation and efficiency of the Patients Digital Health Twin models. This analysis will help in understanding the hardware dependencies of the digital twin system and in making informed decisions for future hardware enhancements.

3.2. Integration with the BRAINE platform

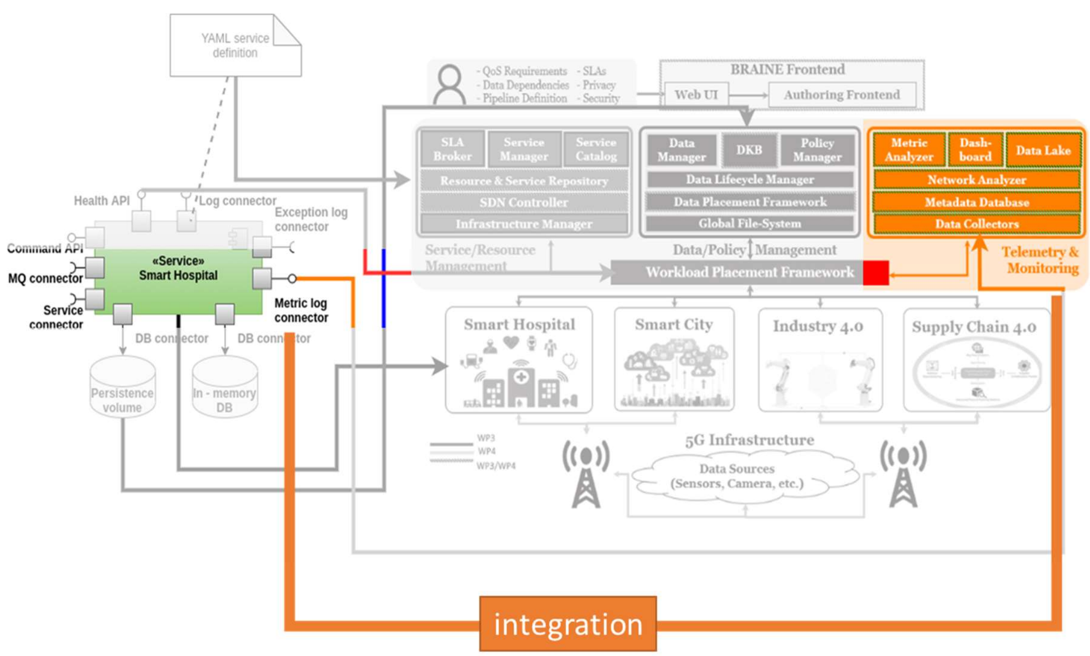


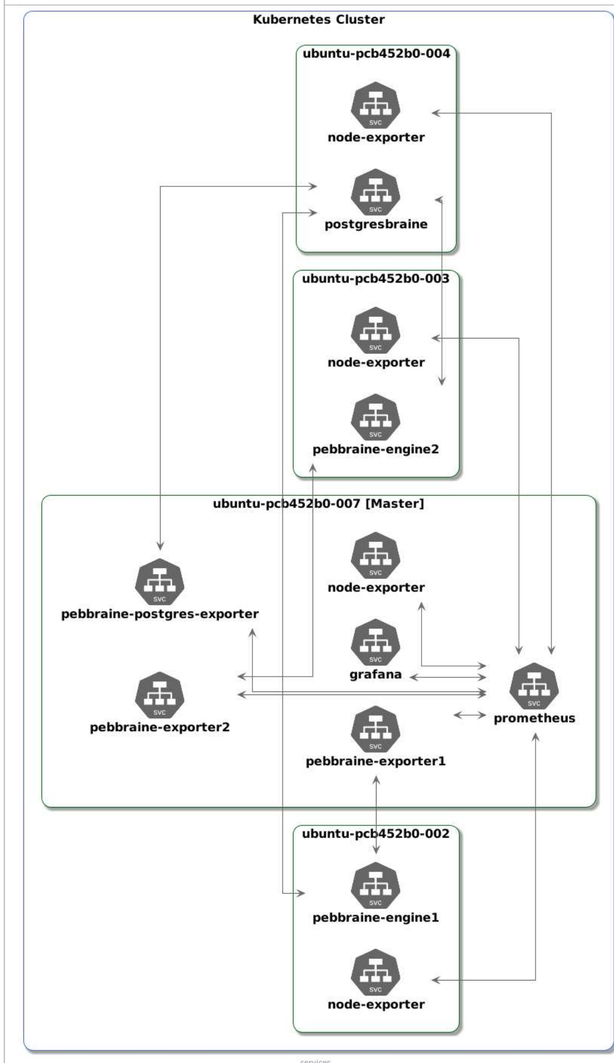
Figure 6 An endpoints added to the Patient Digital Health Twins services and accessed by Prometheus to provide the set of metrics (as required by Prometheus' exporter implementation).

Use Case 1 had the following cluster on BRAINE platform (Table 3):

Table 3 Claster nodes and their short description

Claster 4 nodes	
ubuntu-pcb452b0-002: RAM: 31Gb CPU: 32	ubuntu-pcb452b0-003: RAM: 31Gb CPU: 16
ubuntu-pcb452b0-004: RAM 31Gb	ubuntu-pcb452b0-007: RAM: 31Gb

<table>
<tr><td>CPU: 32
Patients digital twin (peb) system node_exporter postgres have been deployed</td><td>CPU: 32

Master node,
node_exporter
Grafana
postgres_exporter
peb_exporter</td></tr>
<tr><td>
</td><td>node 002 and node 003 patient digital twin system. They communicate with postgresql.

Node 004: runs postgresql.
Node 007: master node .

Monitoring: on all nodes (002,003,004,007) runs Node exporter which is monitoring the hardware.

Node 007 runs Prometheus, Grafana and exporter for patients digital twins and postgres.

2 patients digital twins exporters monitor patients digital twins system

A postgres exporter monitors the Postgresql.

All exporters collect metrics and send them to the Prometheus service. Also, Grafana service is used for the metrics.</td></tr>
<tr><td></td><td>Postgresql is needed to store patients digital twins systems data</td></tr>
</table>

The main characteristics of the experimental system:

Table 4 main figures for patients Digital Health Twin models that run on the EMDC

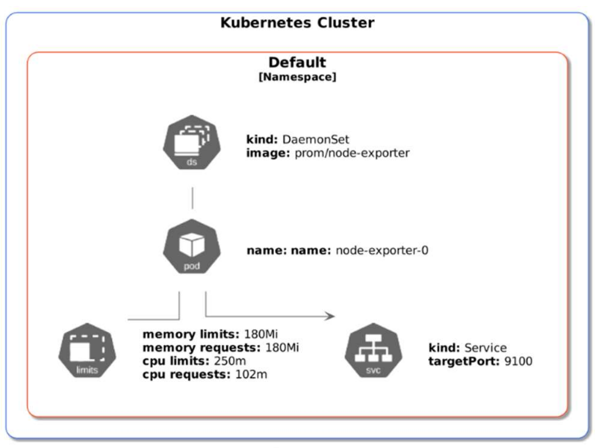
	Total
Patients' Digital Health Twin models	60
Objects	1573
Indicators	7080
Data elements	2280
Sensors	2880

3.2.1. Monitoring System Implementation

The following services were used for the Digital Health Twin cluster monitoring:

- Prometheus: responsible for aggregating metrics from various exporters.
- Grafana: facilitates the prompt visualization of data aggregated by Prometheus.
- Node_exporter: provides hardware-related metrics.
- Postgres_exporter: provides postgresql performance metrics;
- Patients digital health twin exporter: supplies system's performance metrics;

Table 5 Monitoring System Implementation

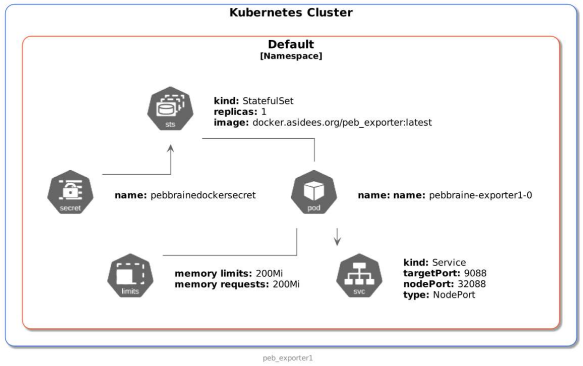
<table>
<tr><th><u>Visual representation</u></th><th><u>Comments</u></th></tr>
<tr><td>


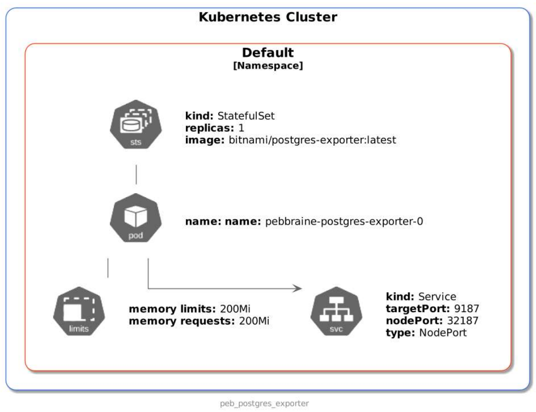
</td><td>

<u>**Node exporter:**</u>

There are 4 instances with Node_exporter deployed in the cluster.

It provides hardware (BRAINE EMDC) metrics.
</td></tr>
</table>





Peb exporter и postgres exporter

Peb_exporter provides metrics from patients' digital twin systems. There are 2 instances run in the cluster.

One is for each patient's digital twin system.

Postgres exporter provides metrics from postgresql.

To effectively track how well Patients' Digital Twins system is running on the BRAIN EMDC, we've created our own set of performance monitoring indicators. These indicators were specially designed to give us a clear picture of the system performance, ensuring we can keep the digital twin system running smoothly and efficiently. Some of these indicators are presented below:

Table 6 Monitoring indicators

	Metric	Name	Type
1	peb_command_error	Number of errors while each command processing	counter
2	pharos_command_queue_size	Number of waiting commands in queue	gauge
3	peb_command_timeout	Number of timeout error for each command	counter
4	peb_crontask	Number of tasks for import	gauge
5	peb_data_element	Total Number of data elements	counter
6	peb_data_element_value	Total Number of data elements values	counter
7	peb_db_up	Is database available: 1 for yes, 0 for no	gauge
8	peb_indicator_status_values	Total Number of indicator status values	counter
9	peb_indicator_values	Total Number of indicator values	counter
10	peb_indicators	Total Number of indicators	counter
11	peb_object_status_values	Total Number of object status values	counter
12	peb_objects	Total Number of objects	counter
13	peb_online_users	Online users	gauge
14	peb_sensor	Total number of sensors	counter

15	peb_sensor_value	Total number of sensor values	counter
16	peb_server_task_size	Total Number of tasks	gauge
17	peb_server_up	Last scrape was able to connect to the peb server: 1 for yes, 0 for no	gauge
18	peb_user	Number of registered users	gauge
19	pharos_command_exec_seconds	Command execution time	gauge

3.2.2. Performance Assessment:

Consequently, each cluster runs thirty patient's digital health twins. The system is configured to import data from sensors and data elements at predetermined intervals. This information is then logged within the database and subsequently utilized to calculate various indicators and objects of monitoring (patient's digital twins).

Table 7 3.2.2. Performance Assessment in figures

	Sensors	Sensors
1 minutes	240	240
10 minutes	450	450
20 minutes	120	120
1 hour	60	60
At 06:00	480	480
At 07:00	30	30
At 09:00	30	30
At 10:00	30	30
Total	1980	1980
Total	3960	3960

The graphical representation of the performance:

On the next chart (Figure 7) we can observe a notable increase in the data imports at 06:00 hours. However, by 06:12 hours, the import process aligns with the expected timeline, indicating timely data import.

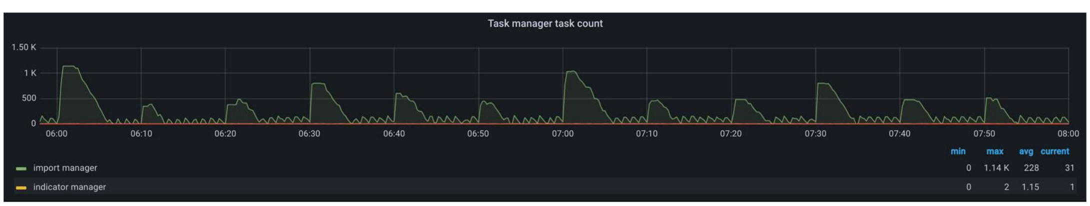


Figure 7 Task manager task counting

The next chart (Figure 8) represents import during of one hour period, we see that a periodic import is within a minute. There is no accumulation of data.

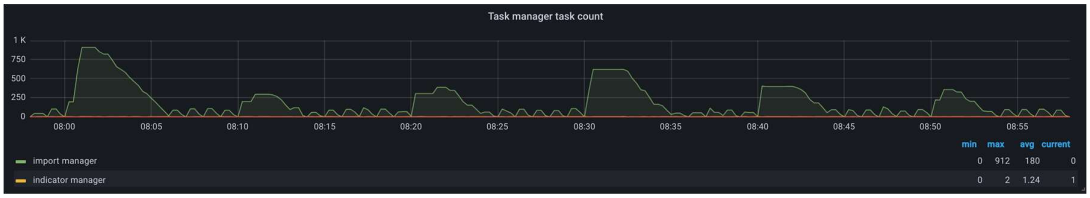


Figure 8 Import manager and Indicator manager

The average execution time per import is 1.28 sec. (Figure 9)

Figure 9 Average execution time per import

The Figure 10 below represents calculation of indicators and states: The data bursts occur after 06:00, this can be explained by the fact that before calculating, it is necessary to collect and analyse the received data. There are no problems with the calculation of indicators and its statuses which are processed and calculated in an acceptable time. There is no accumulation of data due to delays in processing capacity.

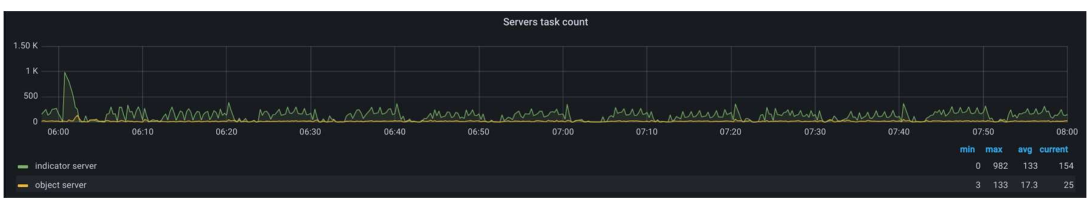


Figure 10 Servers task count

Postgresql as could be seen on Figure 11: The number of connections is normal. The total is just over 100.

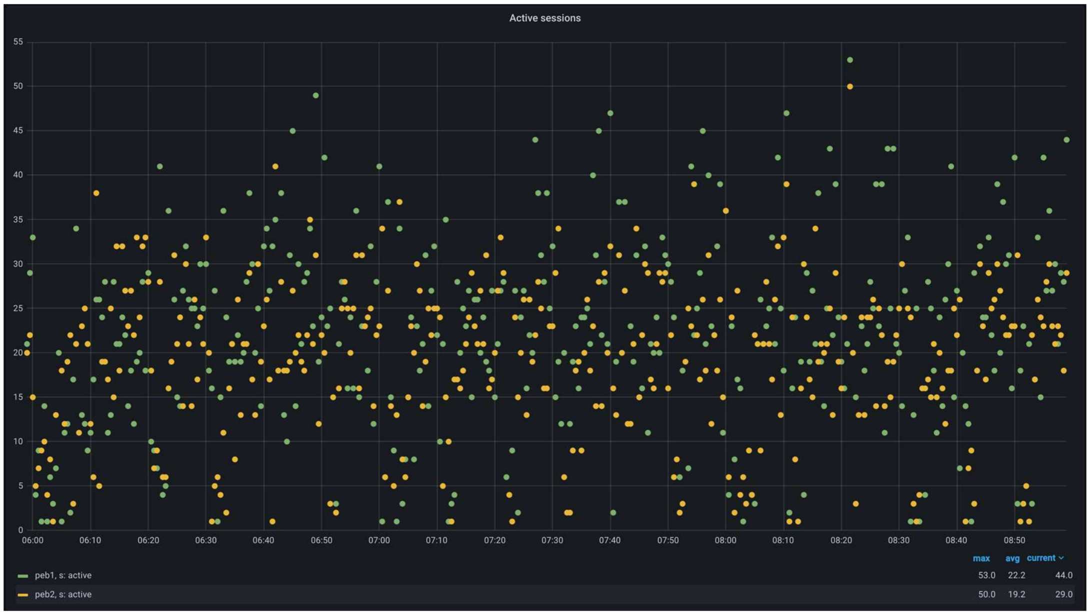


Figure 11 Active sessions

There are no pending sessions (Figure 12)

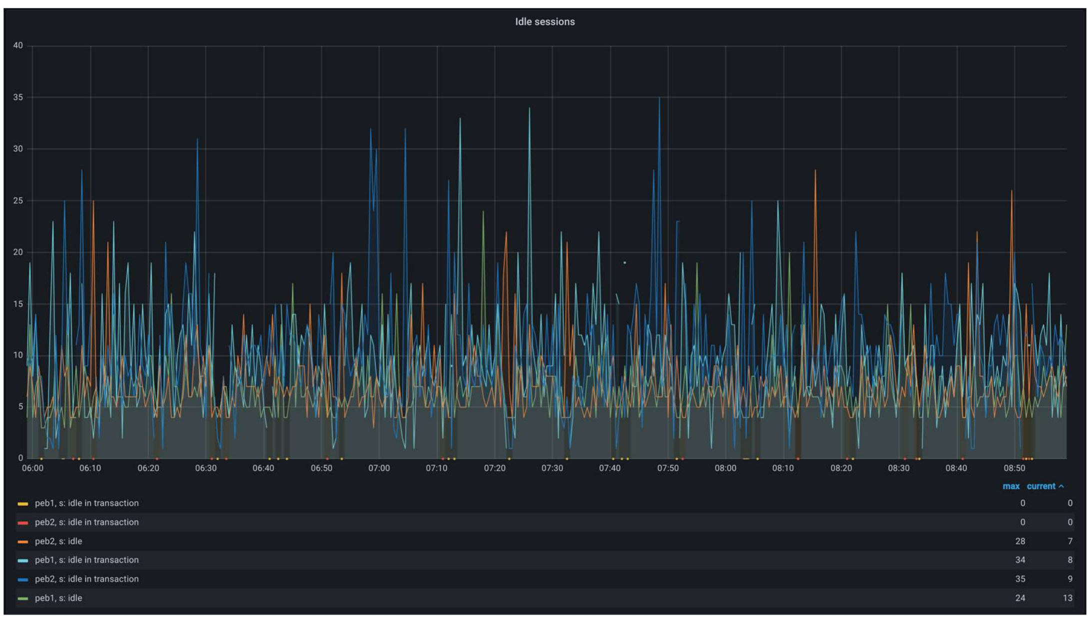


Figure 12 Idle sessions

Within the Postgres system no issues have been identified. In both databases tables' locks remain within normal parameters. There is no evidence of an excessive number of connections. The latency for write transactions is at minimum, and the system's caching efficiency is maintained at 98-99%.

There are no problems with CPU load at Node ubuntu-pcb452b0-002 (Figure 13) or Node ubuntu-pcb452b0-003 (Figure 14),

Figure 13 CPU load

Figure 14 CPU load

However, there is a considerable load on the processor, which primarily could be attributed to “read” operations. Mitigation of this load will require a systematic reorganization and optimization of database queries on our end (UC1).

There are no problems with RAM on node ubuntu-pcb452b0-002 as well (Figure 15)

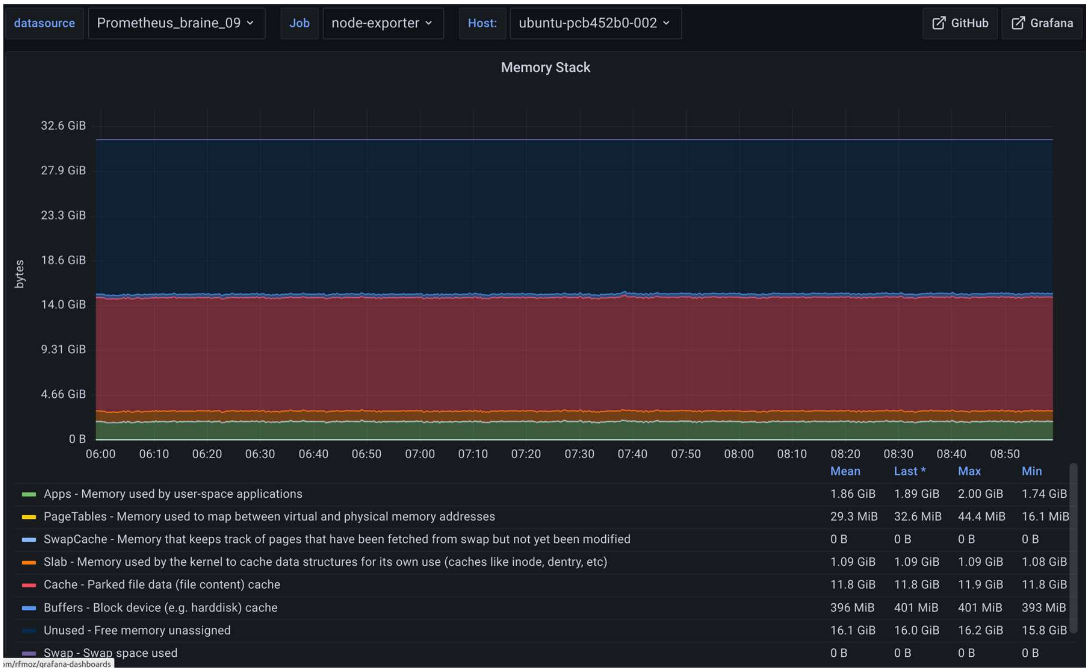


Figure 15 Memory stack

Disk utilization levels are currently within expected operational parameters, presenting no issues (Figure 16).

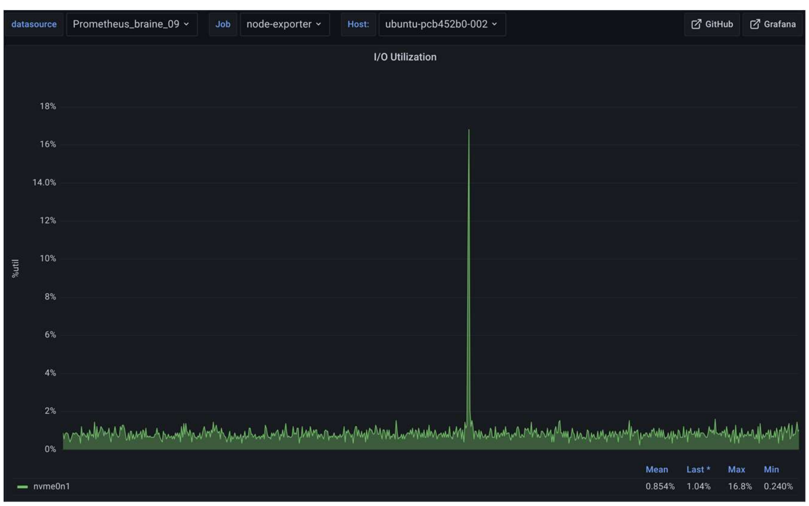


Figure 16 Disk utilisation

Hardware Assessment Summary

Upon analysis of the results, we observed that the master node and the nodes with installed Patients' Digital Health Twin platform exhibit minimal load. However, the node running the Postgres database presents a contrasting scenario. Here, the CPU is subject to considerable load, and the majority of RAM is allocated for caching purposes. Disk usage is recorded at approximately 50%.

This load on the CPU could be attributed to database "Read" operations. Addressing this issue will necessitate a re-evaluation and refinement of database queries from UC1 team. In general, there are no outstanding queries or concerns related the hardware components (BRAINE EMDC) from Use Case 1 perspective.

3.2.3. Summary of BRAINE EMDC Validation by UC1:

Import's frequency and calculation of the indicators and objects statuses are critical for patient's digital health twin functionality as they ensure real-time data accuracy. Such processes enable the digital health twin to maintain an up-to-date representation of the physical patient, which is essential for precise monitoring, predictions, and decision-making support. Without timely imports and calculations, the digital twin's effectiveness, and its ability to support proactive interventions would be significantly diminished.

Upon analysis of the import frequency and the calculation of indicators and health objects, we could note that approximately 1200 imports are processed within a 7–8-minute window. A granular examination has revealed that minute-by-minute imports, along with the calculations of indicators and objects, typically are conclude within a 1-minute timeframe.

From a hardware perspective, no significant load issues have been detected during the validation cycles. The current BRAINE EMDC hardware capacity could accommodate a greater number of patient's digital health twins; however, there is a constraint from UC1 solution namely it is the database capacity. A more thorough consideration of actions registration into database and its optimization is required. This includes examining the efficacy of queries, evaluating potential data redundancies, and experimenting with various configurations within the PostgreSQL environment.

Putting these results into perspective with what BRAINE project and Use Case 1 were trying to achieve within the project scope, we consider BRAINE EMDC as a viable working solution for the healthcare environment. For instance, if a dual-node setup is dedicated to a single hospital ward, the existing infrastructure could potentially support services for at least 60 patients and relevant hospital beds with such DB optimisation.

The relevant metrics and measurements are presented in the Table 8.

Table 8 Metric / Response time (ms)

Metric / Response time (ms)	10 models	20 models	30 models (final validation cycle)
Login (authentication on a server) process	5.6 sec	6.5 sec	9.0 sec
Loading desktop monitor	10.2 sec	11 sec	14 sec
Opening object status history	15 sec	16 sec	8.5 sec
Median delay between a value generation and indicator calculation	12 sec	25 sec	12 sec
Median task queue size for indicator calculation	1-2	1-4	2-4
The median size of task queue to calculate object states	2	2	2-4
Download model	2 min	2.5 min	3 min
Upload model	3,5 min	4 min	3-4 min
Opening a dependency graph for a single patient object	27 sec	28 sec	17 sec

4. Results

4.1. *Patient management platform*

IMC, as a provider of Use Case 1, developed a patients' digital health twins cluster application powered by Pharos Navigator® platform, applying AI/ML algorithms to enhance healthcare services through edge computing integration (BRAINE EMDC). Such synergy allowed a real-time processing of health data (first of all from MIOT) and environmental data, supporting advanced health condition analysis and predictions for each individual patient in the post-operational ward of a hospital. It's designed for many patients monitoring in healthcare facilities like hospitals and caregiving centers.

Patients' Digital Health Twin platform integrates data from diverse medical IoT devices, diagnostics, and wearables, accessible via standard networks such as Wi-Fi and Bluetooth Mesh.

The enhanced BRAINE EMDC platform and Use Case 1 'Healthcare Assisted Living' through patients' digital health twin platform provide a sophisticated, secure, GDPR-compliant, and cost-effective solution for healthcare and caregiving institutions, health insurers, and patients across the EU. The solution focuses on decentralized healthcare, leveraging cutting-edge AI and digital twin technology to deliver a secure, efficient, and reliable service.

4.2. Patient Digital Health Twin

The system of Patient's Digital Health Twins enhances the monitoring of health conditions of each particular patient, for example, in the hospital ward, improving accuracy of the understanding and assessing of each patient's health status, and reducing the need for medical intervention or acting promptly in time.

The eHealth domain is latency-sensitive, where delays can be detrimental to patient's health or even life-threatening. The critical nature of these services consists of latency, privacy, bandwidth, and fault tolerance constraints for handling sensitive medical data.

Evaluating such data streams in close proximity to its sources offers clear benefits, effectively decreasing the challenges posed by off-premises cloud solutions. By processing data on-site (hospital premises), the issues of latency, privacy, bandwidth, and fault tolerance—which are crucial for handling sensitive medical data—are significantly mitigated, enhancing the responsiveness and security of critical healthcare services.

The infrastructure, a network of BRAINE EMDCs, is designed to manage substantial data streams typical in medical settings, aiming to minimize data loss and ensure the continuous operation required by critical applications. It supports the concept of distributed hospitals and medical organizations, allowing clinicians to access meaningful data in real time, mitigating hardware failure impacts, and facilitating near real-time anomaly detection for emergency prediction and identification.

IMC's Use Case 1 involved simulating a decentralized healthcare centre's workloads using anonymized data and evaluating the EMDC's performance.

Digital Health Twin: Driven by data collected from sensors in real time, we use the sophisticated computer model(s) that could mirror almost every process taking place in the target complex system of systems “Many Humans at Hospital Premises”

In the case of a Patient’s Digital Health Twin each biophysical-cyber system model of a human health homeostasis and its management consists of 50 sensors, 21 data elements, 94 biomarkers and other health indicators. Each such model was built from the scratch using Pharos Navigator® IoT platform and its underlying systemic methodology. There are no common methods, standards or norms related to such new technology implementation.

The generic definition of a patient’s digital health twin has not yet settled. Some people think about any 3D models of a body and its specific organs or simulation counts. More ambitiously, others envisage a set of integrated models or software that pairs the digital world with physical assets, with or without live information from sensors. In our UC1 we used the numerical digital health twins which quantitatively represent the complex biochemical processes taking place in the human body according to the existing medical knowledge.

4.3. Implementation of LORA Blockchain protocol for patient sensors

In the hospital environment, medical IoT and its data can revolutionize patient care by providing real-time insights and improving health outcomes putting patients at the centre of care. However, hospital stings and constrains poses significant challenges in ensuring security, privacy, and accuracy while integrating with existing medical systems and with existing medical equipment.

<u>Challenges and constraints that need to be considered:</u>

- Operating in a multi-vendor environment with stringent requirements for data provenance, audit trail and post-hoc traceability of any decisions
- Need for a distributed ledger for capturing data-collection and control events securely in space and time
- Smart low-power IoT devices connected to medical equipment

<u>Edge infrastructure based on an original ***permissioned*** blockchain[2]</u>

- Zero trust, except one sealed, non-Internet-connected, non-programmable unit.
- Powerful witness mechanism for post-hoc verification
- Blockchain server (operating on EMDC)
- Responsible for receiving and pre-filtering ledger records from IoT and cloud clients
- Keeper/manager of a Content-Addressible-Storage (CAS)
- Forms blocks
- Sequencer (sealed, stand-alone, contactless connection only)
- Signs blocks into a chain, prevents chain splitting.
- IoT controllers (LoRa-connected controllers)
- Attached to proprietary medical equipment.
- Produce a signed chain of sensor-data messages.

[2] Shafarenko, A. A PLS blockchain for IoT applications: protocols and architecture. *Cybersecur* **4**, 4 (2021).

- Access and independently validate messages from any other blockchain users[3]
- low power
- Witnesses (LoRa listeners)
- unknown location, purely passive radio (LoRa) listeners
- post-hoc notification of protocol violations
- DoS attack early warning.

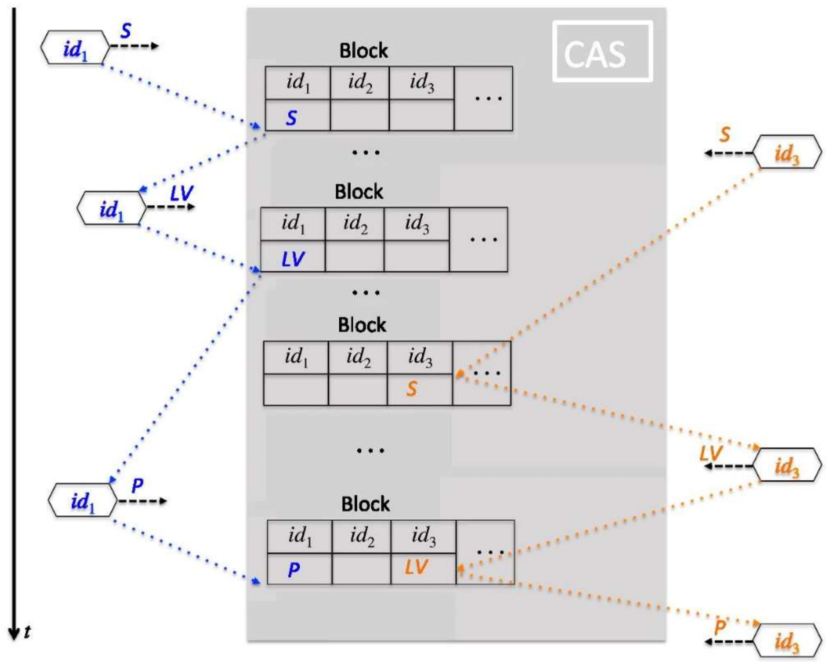
The implemented solution consists of adaptations and optimisations to Byzantine agreement protocols used in KB from D3.1.2 based on findings of physical broadcast effects on edge. Resources collaboration developed in WP2 (T2.3) during BRAINE project implementation.

It was established earlier that the use of LoRa communications ensures stronger resistance to interference by attackers. Due to the "capture effect", the attacker signal has no effect on the legitimate broadcast of the sequencer until the power of the interfering signal exceeds that of the legitimate one by approximately 3db. When this happens, the legitimate signal is completely suppressed by the attacker, rather than distorted beyond the capabilities of the FEC. From the physical point of view, the attack has a hard edge, all, or nothing, so the usual AI based intercept methods are unlikely to provide sufficient early warning at the physical level.

The blockchain communication on which our proposed resource collaboration is based, uses robust protocols to safeguard against such attacks. We developed and analysed a protocol, SLVP, and have found that it has the necessary security properties that give us adequate defence against an "all or nothing" attacker.

The principle of the defence is that the protocol produces a thread of S-,LV- and Pmessages, each of which can be suppressed, but the IoT device monitors the Sequencer's broadcasts and will repeat blockchain submission until the correct message is published intact on the blockchain (see Figure 4.1.1). Only then will the protocol progress to the next message. This would be hazardous, since the attacker is able to insert their own messages spoofing the user IoT device. However, due to the V-part of the LV-message, and a special search algorithm sketched in the Verify column of the last row, the Blockchain server is able to reject attack messages based solely on the preservation of a short-term secret. The cryptography used in this is Post Quantum, hash–based. The SLVP protocol makes it possible to remove intrusion detection from the physical layer (where it is expensive, and resource limited) and rely entirely on the blockchain client-server algorithms.

[3] Shafarenko, A. Indexing structures for the PLS blockchain. *Cybersecurity* **4**, 36 (2021).



Block	Transmit	Verify	BC Action
b_0	$P_1 = H(N_1)$	Out of Band (Enrolment)	Post
b_1	$S_1 = \mathbf{E}^*_{N_1}(H(N_2), M_1)$	—	Post
b_2	$LV_1 = H(N_2) \oplus N_1 \,\|\, H(H(N_2)\|\|N_1)$	—	Post
...	...	...	...
b_n	$P_k = H(N_k)$	*as for* b_{n+3}, *assume success*	Post
b_{n+1}	$S_k = \mathbf{E}^*_{N_k}(H(N_{k+1}), M_k)$	—	Post
b_{n+2}	$LV_k = H(N_{k+1}) \oplus N_k \,\|\, H(H(N_{k+1})\|\|N_k)$	—	Post
b_{n+3}	$P_{k+1} = H(N_{k+1})$	for $b_n < b < b_{n+3}$: find **first** LV such that $H(P_{k+1}\|\|L \oplus P_{k+1}) = V$ **if found in block** $\hat{b}$: **unless** $\exists b \in (b_n, \hat{b}), L' \in B_b$: $H(L' \oplus P_{k+1}) = P_k$ **else**	 Post Reject

Component C2.19 consists of the following units:

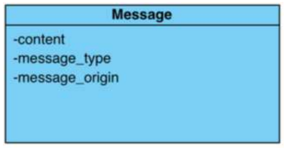
1. PLS blockchain manager
2. PLS sequencer
3. Web client
4. IoT client

Unit 1 is developed using Flask in Python. The solution includes Content-Addressable Store within the server's security perimeter.

Unit 2 is prototyped as part of Unit 1 but will be separated out for uploading into a sealed, sequencer, prototyped as an IoT platform using Bluetooth and LoRa communications.

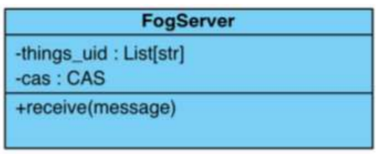
Unit 3 is based on the following API (see Figure 4.1.2 - Figure 4.1.7):

Message



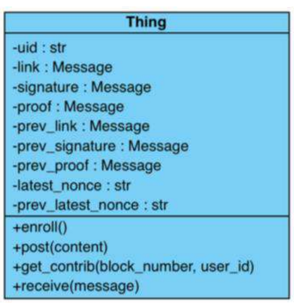
Message types
• PROOF_PLS
• LINK_PLS
• SIGNATURE_PLS
• ENROLMENT
• ACK
• FAIL
• SINGATURE_SLVP
• LINKVERIFY_SLVP
• PROOF_SLVP

Fog Server



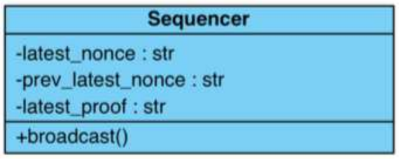
The main method is 'receive', which receives a message and processes it according to its type.

Thing



This is an emulation of the IoT platform.
Methods:
• enroll: register the client in the blockchain
• post: post user content on the blockchain
• get_contrib: obtain a list of contributions and adjunct hashes by user ID and block number
• receive: receive a message and perform action depending on message type

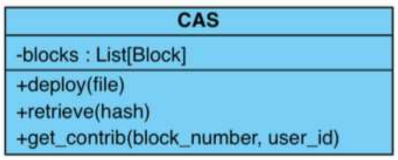
Sequencer



The sequencer class, emulating the PLS blockchain sequencer.
The main method is 'broadcast', intended for sending PLS messages to all blockchain clients.

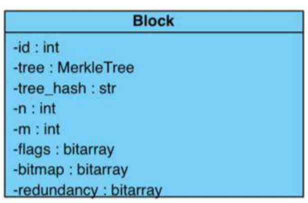
CAS

Content-addressable storage



Methods:

• deploy: deposit a record in CAS
• Retrieve: retrieve a record based on its hash



Block

The class of the block of the PLS blockchain
All classes have been implemented. The Server and the Sequencer use the Python Flask package to support the Web implementation of the API.
Unit 4 has not been developed yet.
The protocol stack and services have been implemented in Python to demonstrate the feasibility of the blockchain solution based on the proposed protocols (See Table 4.1.1).
This comprises subsystems:
• Fog_server
• Sequencer
• IoT blockchain comms library
• CAS

Low bitrate blockchain protocols

The server-side code can remain in Python form due to the low rate of transactions in an IoT swarm, which makes it possible to use interpreted code without risk of a performance bottleneck. However, the IoT blockchain library requires an implementation.
in C++ since that is the language low-power platforms are coded for to achieve the best performance and resource utilisation.

IoT blockchain comms library in C++ is the main outstanding item.
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• CAS

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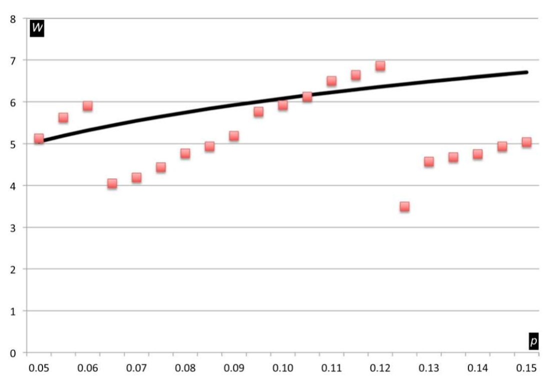
IoT blockchain comms library in C++ is the main outstanding item.

The main problem for an underpowered IoT platform in using a block chain is access to the blocks. Since the platform is communication-challenged (duty cycle of 1% or down to 0.1% on LoRa with a maximum of 50Kbits/sec, effective indexing is the key issue (see [Shafarenko1]). We researched available indexing structures of the blocks and developed an original one, the Merkle-Tunstall (MT) Tree, using which it has become
possible to reduce the communication load to suit the available bandwidth.



The vertical access is the average path length W from the root (which is the Root of Trust) to a leaf for a swarm of 1024 IoT devices. The horizontal axis is for the probability p for a given IoT device to contribute to any given block. We can see that the amount of communication (scattered dots) for the MT is typically better than the standard MerklePatricia Trie (MPT, solid line). At the same time, MT is a zero-cost solution for proofs of absence. At p~0.1, the search for records is zero cost in 90% of the blocks, and in the 10% it is on a par or better than the standard MPT. This demonstrates that our solution is up to an order of magnitude better than MPT (see [Shafarenko2]).

5. Impact

5.1. Comparison to existing systems

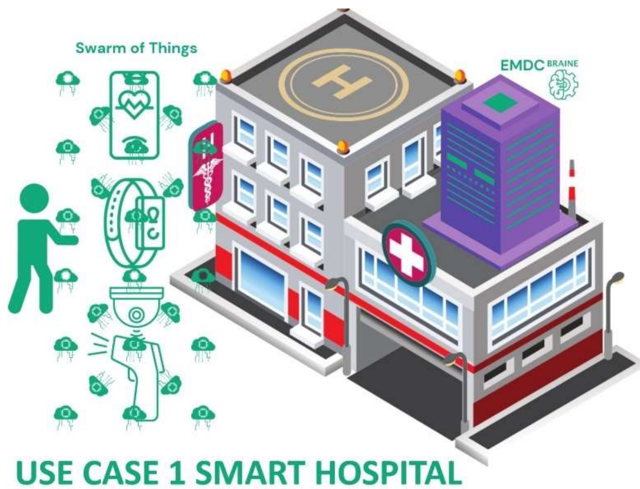
BRAINE EMDC—edge micro data centre running a cluster of many patients' digital health twins—represents a significant advancement over existing systems in the following aspects:

- Unlike traditional data processing methods which rely on centralized cloud services, BRAINE EMDC system processes data locally at the edge, leading to faster response times and improved efficiency in healthcare applications.
- Traditional systems often lack flexibility. In contrast, BRAINE EMDC solution offers customizable and scalable options, making it suitable for various healthcare settings, from small clinics to large hospitals.
- While existing systems sometimes suffers with data security and privacy concerns, especially in cloud-based architectures, our edge-based approach enhances data security and ensures better compliance with healthcare regulations like GDPR.
- Existing systems may not effectively support real-time data analysis. Our digital twin technology enables real-time monitoring and predictive analytics, offering a more dynamic and responsive healthcare experience.
-

Table 9 Comparison EMDC vs cloud computing

Points of difference	**EMDC**	**Cloud computing**	**Comments from UC1 perspective**
Operations	EMDC computing happens on the EMDC itself.	Cloud computing happens on cloud platforms such as Google Cloud, AWS, etc.,	Edge computing works best for IoT devices and sensors, which is relevant for UC1 and healthcare.
Benefits	Owner can independently scale the network / EMDC with each new device that is added to the system.	User can store a massive amount of data on scalable hosting over internet access and access it anytime.	Near real-time, since EMDC eliminates delays and slow response times and works on providing quick results.
Suitable Use Cases	Edge computing could be a perfect match for healthcare environment with sensitive patient's data and GDPR constraint.	Cloud computing suites business that requires huge amounts of data storage and need scalable and cost-effective hosting providers.	EMDC provide compliance with the GDPR as edge computing provides geofencing and processes data on local networks, which is important for healthcare setting.

5.2. Potential impact to the healthcare sector



The concept of a digital twin in healthcare is still in its early stages and was not widely adopted yet. There was progress in these approach on TRL1-3 stages. Many studies and conceptual frameworks were exploring the idea of digital twins in healthcare, leveraging advances in AI, data analytics, and IoT. There are also TRL 4-5 'Lab Testing/Validation' initiatives as well. However, TRL 6-7 'Prototype Development and Clinical Testing' are not widespread. While TRL 8-9 'Full Scale Implementation' innovations were not yet at full-scale implementation of digital health twins in hospitals.

The concept of patient digital twins that can run on the edge EMDC in healthcare could have a transformative impact on the healthcare industry. Here are some of the ways to impact the health care domain with such solutions (‘BRAINE EMDC+Patient Digital Twins cluster):

- Personalised Medicine: patient digital health twins can help in creating personalised treatment plans for patients by using their individual physiological data to simulate how they would respond to different treatments.
- Predictive Analysis: patient digital health twins could potentially predict future health deterioration by analysing real-time data from wearable devices and electronic health records and the relevant historical time-series.
- Improved Outcomes: by modelling disease progression and treatment responses, healthcare providers can make more informed decisions, potentially improving patient outcomes.
- Efficient Use of Resources: Predictive capabilities could help healthcare systems to better allocate resources by anticipating patient needs, which could lead to cost savings.
- Patient Empowerment: Patients could have better access to, and understanding of, their own health data, empowering them to be more active participants in their care.
- Telemedicine and Remote Patient Monitoring: Digital Health Twins could significantly enhance telemedicine and remote patient monitoring capabilities, making it easier to manage chronic conditions and provide care in remote areas after their release from the medical facilities.
- Medical Training and Education: Digital health twins can serve as advanced tools for medical training and education, offering students and doctors a safe and controlled environment to learn and test their skills.

While the potential benefits are significant, it's important to note that there are still also challenges to be addressed, including data privacy and security, ethical considerations, regulatory compliance, and the need for standardisation and interoperability between different health systems and technologies.

5.3. Advantages of the BRAINE platform

The healthcare industry is on the way to integrate advanced technologies such as 'BRAINE EMDC + Patient's Digital Health Twins cluster', although not without some challenges e.g., data aggregation and its management to regulatory compliance (GDPR) and industry-academia collaboration. In this context, BRAINE project provides solutions and advancements that could stand out, offering a range of benefits that directly address some of the challenges:

- As a tool that address efficient data collection and processing.
- Offering a solution that can merge disparate data types effectively.
- Serving as a platform that can bridge the gap between industry and academia and foster joint ventures, leading to more innovative and applicable technological solutions in healthcare setting.
- Shifting the focus from pure academic research to practical implementation of patients' digital twins, alongside modelling technique enhancement.
- Supporting tools and platforms that provides the shift towards personalized healthcare, allowing for more tailored and effective treatment and care.
- Enhancing the converge of digital technologies with healthcare, bringing efficiency and precision in healthcare delivery.
- Being in regulatory compliance to ensure GDPR adherence as well as to other relevant data protection regulations, safeguarding patient privacy and data security.
- Reducing logistical and operational challenges within healthcare facilities.

- *All in all, the European Union has some 15 000 hospitals, which account for 25% to 60% of health expenditures depending on the country.*

The implementation of our BRAINE EMDC with patients' digital twin technology presents key advantages, namely in terms of cost-effectiveness and scalability, making it a working solution for hospitals that are looking to upgrade their ICT infrastructure with minimal capital investment:

- BRAINE EMDC could be a starting initial investment, requiring minimal upfront capital investment. This makes it accessible even for smaller hospitals or those with limited budgets.
- We aimed to set a trial-friendly deployment, allowing hospitals to test and evaluate its effectiveness without committing to a large-scale implementation. This trial phase could help in assessing the benefits and integration with existing systems.

- BRAINE EMDC is modular solution, meaning that a hospital can start small and scale it up as needed. This modularity avoids the need for a large initial expenditure.
- Important part is scalability, since as the hospital's needs continuously grow, BRAINE EMDC technology can scale up accordingly.
- Cost savings in the long-term reducing reliance on remote cloud services, hospitals can save on operational costs over time.
- BRAINE EMDC brings minimal disruption in its implementation as the edge micro data center.
- It supports smart hospital features with the many patients' digital health twins which can be incrementally adopted.

BRAINE "EMDC + Patients' Digital Health Twin cluster" approach allows hospitals to start utilising the advanced healthcare technology, enhancing hospitals' capabilities as a smart hospital, with manageable investment and the flexibility to grow and adapt as their needs evolve.

5.4. Business solution and economic advantages of BRAINE for healthcare

The market growth in edge computing within the healthcare sector is showing a significant upward trend. Here are some key statistics and projections that highlight this growth:

- The Global Edge Computing in Healthcare Market size is expected to reach $25.5 billion by 2030, rising at a market growth of 26.9% CAGR during the forecast period. (Global Edge Computing in Healthcare Market Size, Share & Industry Trends Analysis Report By Component, By Application, By End User, By Regional Outlook and Forecast, 2023 – 2030)[4]
- The global edge computing market size was valued at USD 11.24 billion in 2022 and is expected to expand at a compound annual growth rate (CAGR) of 37.9% from 2023 to 2030. Edge computing adds a layer of complexity to organizations by enabling a diverse set of stakeholders to maintain IT infrastructures, networking, software development, traffic distribution, and service management. Edge also combines software, hardware solutions, and networking architecture to cover various use cases in several businesses. (Edge Computing Market Size, Share & Trends Analysis Report By Component (Hardware, Software, Services, Edge-managed Platforms), By Application, By Industry Vertical, By Region, And Segment Forecasts, 2023 – 2030)[5]

Such growth shows the increasing needs and investment in edge computing within the healthcare sector, driven by the demand for more efficient data processing and management in medical applications. The high growth rates suggest a rapidly developing market with significant potential for future expansion.

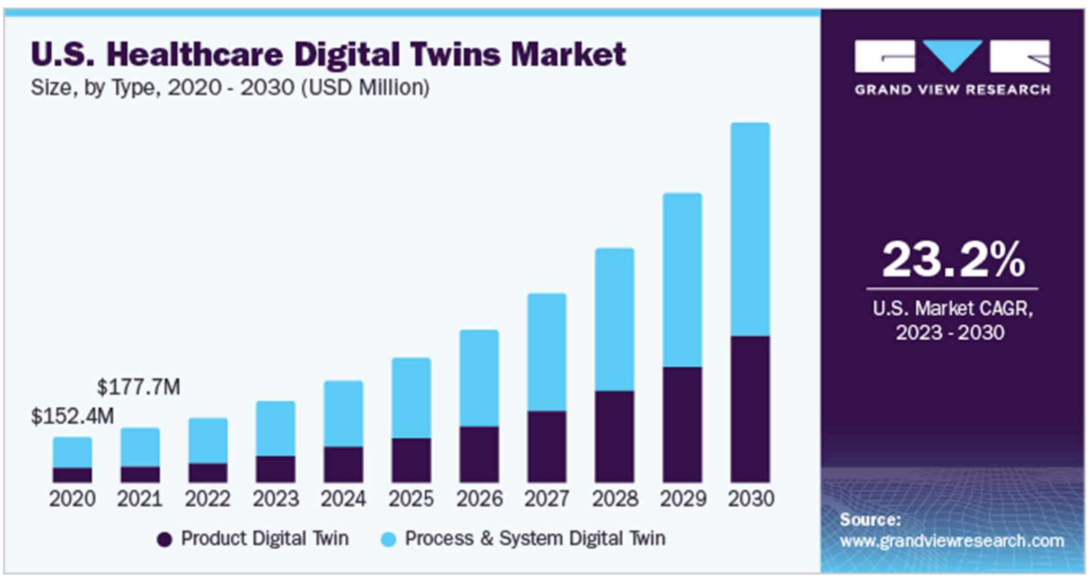
On the other hand, there is a market for digital health twins in healthcare, which is also experiencing rapid growth. The market's growth reflects the increasing adoption of digital twin technology in healthcare, driven by its potential in enhancing personalized and predictive patient care.

[4] https://www.reportlinker.com/p06487799/Global-Edge-Computing-in-Healthcare-Market-Size-Share-Industry-Trends-Analysis-Report-By-Component-By-Application-By-End-User-By-Regional-Outlook-and-Forecast.html?utm_source=GNW

[5] https://www.grandviewresearch.com/industry-analysis/edge-computing-market#:~:text=Report%20Overview,IT%20infrastructures%2C%20networking%2C%20software

- The global healthcare digital twins market size was estimated at USD 572.4 million in 2022 and is projected to grow at a compound annual growth rate (CAGR) of 25.6% from 2023 to 2030. In healthcare, digital twins are employed to create digital simulations or models that replicate various aspects of healthcare information, including hospital environment, human physiology, and lab results. The representations help to improve efficiency, anticipate future demand, and optimize costs. The aforementioned factors are anticipated to drive the demand for the technology during the forecast period. (Healthcare Digital Twins Market Size, Share & Trends Analysis Report By Type (Process & System Digital Twin, Product Digital Twin), By Application (Personalized Medicine, Drug Discovery), By End-use, By Region, And Segment Forecasts, 2023 – 2030)[6]
- Opportunities abound in the Digital Health Twin in Healthcare market, with the potential to drive substantial advancements in patient care. As healthcare providers and technology companies continue to collaborate, the market is poised for growth in areas such as remote patient monitoring, disease prediction and prevention, and drug development. Leveraging artificial intelligence and machine learning, digital health twins have the potential to transform healthcare into a more proactive and patient-centric industry. (Digital Twin in Healthcare Market Revolutionizing Patient Care 2023 to 2030 | Philips, Siemens, Dassault Systèmes, GE)[7]

Figure 17 U.S. Healthcare Digital Twins market



BRAINE EMDC with the patients' digital twins on top of it offers healthcare sectors a practical 'ready for the implementation' use of edge computing and aligns well with the market's rapid growth and evolving demands. This growth highlights the current needs and investments in edge computing within healthcare, that are also supported by the necessity for more efficient data processing, management in medical applications and developments in Medical IOT. BRAINE project not only matches with it but also advances beyond the current state of the art.

[6] https://www.grandviewresearch.com/industry-analysis/healthcare-digital-twins-market-report#:~:text=The%20global%20healthcare%20digital%20twins,from%202023%20to%202030
[7] https://www.digitaljournal.com/pr/news/cdn-newswire/digital-twin-in-healthcare-market-revolutionizing-patient-care-2023-to-2030-philips-siemens-dassault-systemes-ge#:~:text=The%20worldwide%20Digital%20Twin%20in,also%20shows%20the%20importance%20of

6. Conclusion

In conclusion, the deployment of BRAINE EMDC coupled with patients' digital health twin technology represents a significant step forward to the implementation of the Smart Hospital concept. The project demonstrated that EMDC can be tailored to meet the unique challenges and demands of the healthcare sector. Integration of the 'EMDC+ Patients digital health twins cluster' offers an accessible, cost-effective path for hospitals of all sizes on their paths towards smart healthcare infrastructure. The modular and scalable nature of the EMDC technology ensures that even small hospitals can embrace on this shift with a minimal initial investment, benefiting from the features that offers EMDC and expanding the system as hospital's needs grow.

BRAINE project has successfully demonstrated and proved the feasibility and advantages of its innovative approach, also aligning with the current market trends towards more efficient, personalized, and digitalized healthcare. By facilitating real-time data processing, enhancing patient care through digital health twins, and ensuring compliance with GDPR, such solution sets a new benchmark in healthcare technology.

There is also a room for further expansion and refinement of the technology. As hospitals will continue put patient at the centre of care, they will need embrace digital transformation, our services as EMDC and digital health twin technology will play a pivotal role in providing a more efficient, effective, and patient-centred healthcare delivery services.

BRAINE project not only aligns with current healthcare trends but also paves the way for future innovations, ensuring that healthcare providers can continue to deliver high-quality care in an increasingly digital world.

It's important to highlight the successful collaboration between regional funding bodies from all over European Union and the ECSEL (now is KDT JU) has not only provided joint funding for innovative BRAINE project but also created opportunities for small and medium enterprises (SMEs) like IMC from Slovakia to work alongside academic institutions like CNIT and major industry players like DELL. This support has been crucial in advancing technology provided by IMC. Setting further funding specifically aimed at new technologies like edge data centres with patient digital health twins in healthcare would be extremely beneficial. Such targeted investment could be a key to speeding up the development and adoption of the technological advancements at the European healthcare sector. Support on that level would significantly boost the ability of healthcare providers to utilize state-of-the-art technology for enhanced patient care and maintain operational efficiency and benefiting directly from the contributions of SMEs and other partners.