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A Digital Twin Ecosystem for monitoring and KPI analysis in a surgical department

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"If you love what you do and are willing to do what it takes, it's within your reach. And it'll be worth every minute you spend alone at night, thinking and thinking about what it is you want to design or build. It'll be worth it, I promise"

Steve Wozniak

Introduction

In recent years the healthcare has seen a general digital transformation in order to improve the quality of the services delivered, material and staff logistic, specialistic visits and surgeries planning and last but not least creating a more patient-centric vision, to give the necessary importance to his hospital journey. The application of cutting edge and innovative technologies lead to find new ways to manage complex environments like hospitals, such as creating a more interoperable healthcare and new performance monitoring systems: these two simple things could indirectly bring an optimization of internal and external processes and interaction between multiple stakeholders, like different hospitals or doctor-patient communication. This can be helpful with many pain points in healthcare, such as:

- Waiting lists management to guarantee a coherent waiting time for pending surgeries, optimize the call and recall procedures and monitoring the score of each patient related to its priority level, analyze the number of patients beyond the threshold to better understand the current situation and what to improve

- Monitor every stage of the surgical journey over time to understand bottlenecks, advantages and disadvantages of current internal procedures and continuously evolve aiming for better patient care

- Real time visualization of the current state of the hospital and its multiple departments, such as the surgical one

Each health system has its own metrics to measure and calculate performance of different types, so data collection and processes monitoring becomes crucial to give the correct vision of the reality and supporting the directive staff to take decisions. This is valid in every healthcare area, for example hospitalization rooms, clinics or surgery

departments, where real time monitoring of patients is critical to detect anomalous situations and give a support to mitigate all the possible risks that could happen.

The operating room is a particular environment that needs to be under certain conditions in order to guarantee the patient's safety: if something is wrong than it must be notified as soon as possible to ensure a secure and correct surgery procedure. Inside a modern operating room we can find one of the most technological and complex site of a hospital, including devices and sensors for tracking patient's vital signs, air ventilation systems, automatic temperature adjustment and so on. The main problem is that this high level of technology is mixed with old procedures and a operative fragmentation, in fact many systems work like silos without integration. This is why digitalization is so important to transform multiple operating rooms into a cohesive and smart surgical department, exploiting the integration of new technologies such as Internet of Medical Things (IoMT) to connect sensors over the internet and use data aggregation to monitor and make predictive analysis.

Another key point for the evolution of the surgery department lies in the simulations, offering powerful tools to train people about procedures and risks and also give a new operative paradigm for a better management and efficiency. Operating rooms are a high risk locations where the human error can have fatal consequences and a well organized department is important to reduce and mitigate any possible risk, and here it comes the simulation, enabling us to test a specific scenario and improve the global management:

- Simulate the peri-operative journey of a patient

- Test the behavior in case of a virtual anomaly during a specific intra-operative procedure

- Allocate the correct number of surgeons, nurses and professional figures to optimize the surgeries execution

- Increase the utilization percentage of operating rooms and recovery beds (bed management) to avoid waste of resources

- Identify bottlenecks and improve workflows and logistics, simulating rooms turnover, disinfection times, urgent surgeries or even emergencies

The next possible chapter of digitalization is represented by Digital Twin, that is much more than a simulation: we can think about it as a dynamic digital replica of any physical asset, with an arbitrary level of detail and fidelity. We can model everything is interesting for our purposes, such as an entire surgery department thanks to the composability characteristic, creating multiple digital twins within a common environment. This could lead the realization of a new smart and predictive healthcare ecosystem, offering full interoperability between organizations and a better patient focus, aggregating data from different sources for a holistic vision.

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Chapter 1

Digital Twins

What are Digital Twins? This is a question that is as simple as it is interesting, this is the entry point for a new vision of the reality and possibly a cutting edge technology for many industries. As the name says, it is not only a digital representation of a physical asset, but more than that: it can be imagined like a complementary entity that forms a all one entity with the physical asset, or multiple physical assets, combining the physical world and the digital one.

1.1 The story behind the technology

First of all let's introduce how this technology is born, the evolution and what was the original goal to better define all the possibilities and opportunities it is able to unlock.

1.1.1 NASA Apollo Program

The concept of the Digital Twin, a dynamic virtual replica of a physical entity or system, has undergone a significant evolutionary journey from theoretical ideas to a pervasive technological paradigm. The first idea of Digital Twin was proposed by the american space agency NASA, way back in the 60s: these were important years, of great technological as well as military ferment due to the Cold War. Most of all, the so called space race has mobilized huge investments in technological progress in order to reach the lunar surface as soon as possible and put a man on its land. And here comes the famous Apollo program, especially the Apollo 13 mission, where we can see the first

application of a digital representation of a physical asset: model the actual spacecraft and its components with high fidelity and detailed models to better simulate its behavior in specific environments and scenarios, explore different solutions and predict results [1].

In the NASA facility 15 complex physical and digital simulators were used to train astronauts, simulate and analyze every single aspect of the mission and create failure scenarios to study how the spacecraft and each recovery component would behave in a virtual environment as similar as possible to the real one. This is one of the most important aspect, the realistic modeling of the physical component and its intrinsic customizable feature (fig. 1.1), that allows to customize and configure the digital representation with pre-configured or particular configurations to analyze and test the behavior, comprehend wrong decisions, adjust and repeat. The NASA's primitive Digital Twin had an impor-
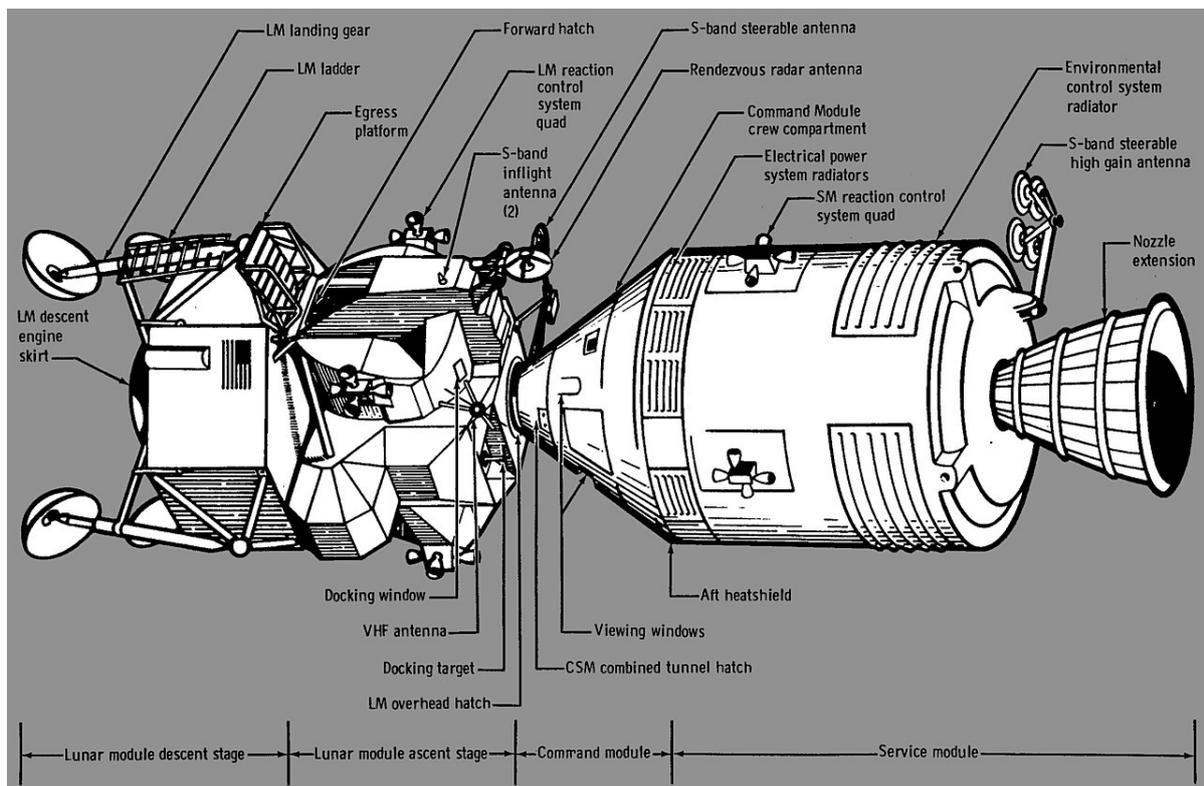
Figure 1.1: The complex Apollo spacecraft in the docked configuration

tant role during the Apollo 13 mission, especially after the oxygen tank explosion in the Service Module, that causes several damages to the spacecraft and a significant loss of oxygen. The agency used all these simulators and digital vehicle modeling to evaluate

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the possible reasons of the accident and to produce and test solutions for the astronauts' survival, due to the sudden uninhabitability of the module and the subsequent transfer to the Lunar Module using it as a lifeboat for life support, propulsion, and navigation. Because of that the importance of the simulation and prediction are fundamental to recover from a failure situation with digital copies of the physical entities we are considering and propose solutions in the fastest and safest way possible, such as re-planning the journey back to Earth exploiting the Lunar orbit to slingshot [2] [3].

The evolution of this approach is the continuous tracking of the real spacecraft within its digital representation managed by the communication center on Earth, unlocking new potentials (fig. 1.2):

- Tracking all sensors data to create a digital coherent state of the spacecraft

- Observe the mission, simulate possible trajectory and make or suggest corrections with the space crew with real time communications

- Use artificial intelligence to predict possible behaviors of the spacecraft to better understand the health of the spacecraft and prevent possible damages that could lead to disasters

- Possible augmentation of the spacecraft capabilities, where the digital part and the physical part are closely linked to each other developing new functionalities, for example real-time analysis of the telemetry to make corrections to the physical spacecraft, aggregate the crew health states to have a full composed view of multiple physical entities and take actions and so on

1.1.2   Mirror World

A Mirror World is a concept first popularized by computer scientist David Gelernter. It refers to a digital representation of the real world that is structurally identical to it. Unlike virtual reality (VR), which may create entirely fictional environments, a Mirror World maps the physical world into a digital medium with extreme precision [4].

- Real-world Mapping: every building, street, and physical asset has a corresponding digital coordinate. It is essentially a "1:1 scale" digital map of reality.
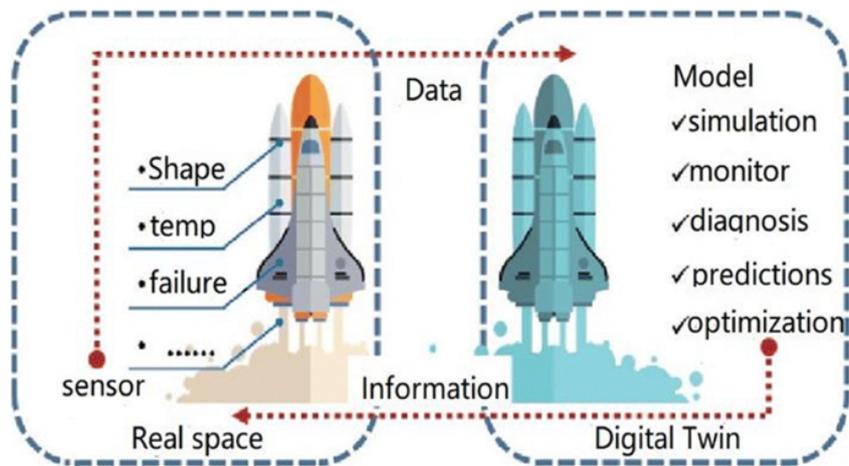
Figure 1.2: Nasa's virtual model concept

- Dynamic Data Integration: it is not a static 3D model. Through the Internet of Things (IoT) and sensors, it reflects the current state of the physical world in real-time (e.g., traffic flows, energy consumption, or human movement).

- Social and Functional Layers: it often incorporates information layers, such as social interactions, historical data, and administrative records, making it a "living" document of human activity.

While the terms are often used interchangeably, there is a subtle difference in scope: Digital Twins usually focuses on a specific object, machine, or process (a Digital Twin of a single operating room or a turbine), while Mirror World represents a macro-system. It is the aggregation of many Digital Twins and datasets to form a comprehensive digital version of a city, a country, or the entire planet.

1.1.3 Formalization of the concept

Thanks to the Nasa's research projects, John Vickers and Michael Grieves, the first concepts of a Digital Twin were shaped and nowadays we are able to use them in strongly improved and complete technologies, enhanced with cloud computing and AI. Grieves initially talked about Product Lifecycle Management using the Information Mirroring Model term, that means the two systems (physical and virtual ones) would be continuously linked, throughout the entire lifecycle of both: an integrated, information based

approach to model physical entities and ecosystems, from the design through all related processes [5]. While Grieves initially called it the "Conceptual Model of PLM", it was the collaboration with Vickers at NASA that led to the formal adoption of the term "Digital Twin" in the 2010 NASA Roadmap and the first three fundamental components:

- Physical Space: the actual object or system existing in the real world (e.g., a satellite, a factory floor, or a wind turbine).

- Virtual Space: a high-fidelity digital representation that contains all the geometry, physics, and behavioral data of the physical counterpart.

- The Data Link: the "bridge" consisting of data flowing from the physical to the virtual (sensors) and information/commands flowing from the virtual back to the physical (actuators or human intervention).

These three principles laid the foundations of the powerful and multi-purpose Digital Twin technology, that has evolved over the year and now transforming fields like Internet of Things and agent-based programming paradigm.

1.2   What is a Digital Twin

Based on what was discussed in the previous sections, let's now see what a Digital Twin actually is, referring to NASA's 2012 definition [3]:

> A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.

We can imagine a Digital Twin like a virtual representation of any interesting object at any abstraction level, linking the real and the virtual worlds together with real-time synchronization, mapping its domain with properties, events, actions and relationships, allowing to have detailed models and a much more realistic and precise simulation of unpredictable scenarios. This definition can be expanded with all sort of material and immaterial things, such as aggregation of concepts or processes: we can track physical asset state or complex processes execution, vehicles, cities and human people, this is

not just a purely descriptive and modeling approach, but the Digital Twin also represents a behavioral approach capable of simulating the dynamics, monitoring the state, controlling or predicting the behavior of a physical asset.

1.2.1 Key concepts

Digital Twins exist to create a mirroring of the physical world, describing assets in terms of properties, events and relationships, so basically we need a Physical Asset (or Object) to represent linked with its own digital representation (or Logical Object). Ideally, these two entities communicate to each other with defined data flows, so the first three key concepts to describe before delving into Digital Twins are the integration levels [6] (fig. 1.3):

- Digital Model: this is the typical virtual representation of a physical entity, asset, system or process, typically created during the design phase and relies on manually generated data and both manual data flow, from the PO to the LO and viceversa from the LO to the PO, without any automated data exchange and requiring the human intervention, resulting in a strongly static representation useful for simulations and what-if scenarios with predefined assumptions.

- Digital Shadow: this concept extends the Digital Model with automated unidirectional data flow from the PO to the LO, while the data flow directed to the physical entity remains manual. For example sensor data and operational information from the physical asset are automatically transferred to update the digital representation, that is the shadowing of the PO, becoming well suited for monitoring and diagnostics.

- Digital Twin: this extends the previous concepts with a bidirectional and continuous data exchange between the physical entity and the digital counterpart, with automatic and real-time data flows from both, defining a new type of representation capable to actively influence the physical system and implementing optimization strategies, decision making and predictive functionalities. This is more an integral part of the overall system than a representation.

Another level of Digital Twin analysis is aligned to the product life-cycle, expanding the concept introducing the Digital Twin Prototype (DTP) and the Digital Twin Instance
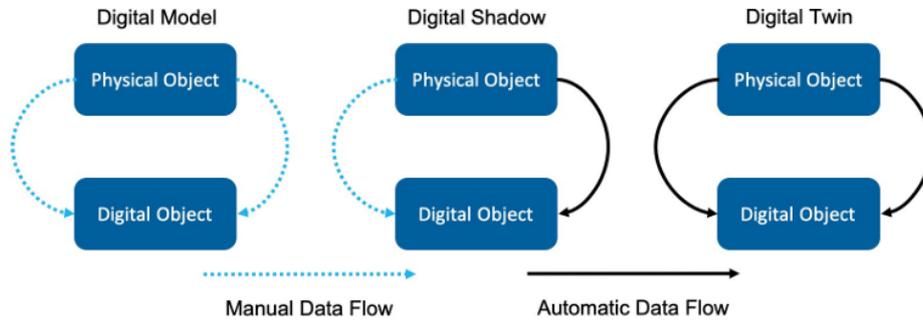
Figure 1.3: Digital representations

(DTI) concepts [5]. Following Grieves' definition, the Digital Twin can be seen as a set of virtual information constructs capable of fully describing the physical product being manufactured, with the same level of detail we would obtain by inspecting the physical object. The Digital Twin Prototype is the initial phase of the Digital Twin: it defines all the information needed to describe and produce the physical asset, the prototype capable of generating multiple copies of the real object. This represents the Digital Twin during the design and development phase, before the physical asset is realized, so it is not linked to any operational data. It contains information like models, requirements, description of properties, 3D models and so on. Then we have the Digital Twin Instance, that is the virtual version of the actual physical object manufactured (based on the prototype) during the deployment phase for example, which is continuously updated with real data from sensors and data flows, reflecting the specific configuration and state of its corresponding physical asset. The Digital Twin Aggregate represents a collection of multiple Digital Twin Instances: an example is the aggregation of data from different or similar assets which are linked to each other with some sort of relationships, enabling high-level analysis and benchmarking. Finally, the Digital Twin Environment, where both the DTI and DTA exist within, provides the infrastructural and contextual framework and the virtual space in which they operate. In this sense, the Digital Twin Environment acts as the enabling ecosystem rather than a Digital Twin itself.

1.3 Characteristics of Digital Twins

While the Digital Twin concept is often introduced at a conceptual level, its practical realization depends on a set of well-defined technical characteristics, and among these, shadowing and lifecycle management play a central role, as they determine how accurately and persistently the Digital Twin represents the physical system over time. A rigorous analysis of these aspects is therefore essential to move from abstract definitions to implementable and verifiable Digital Twins, starting from the fundamental properties that characterize them, derived from the state of the art [7].

Representativeness and Contextualization The logical objects must represent the status and functionality of the physical counterparts and only information and functionality relevant to the context of use should be considered. It's important for the LO to be as much as possible true to the original PO with high level of fidelity and similarity. We can also contextualize the logical object if we need only a subset of all the descriptive information of the PO, considering only relevant attributes we need for our application scenario.

Reflection A PO can be uniquely represented using the attribute values, state and behavior of its LO. This property refers to a mapping of all the information that fully describes the PO with respect to our context and goals. Because the information may change over time, all the meaningful attributes, status, events, actions and relationships that describe the PO must be timely represented by its logical object.

Entanglement Entanglement, as the word suggests, refers to the need for instantaneous (or very close to real-time) information flow between the PO and the LO replica. This can be obtained considering the following three properties:

- Connectivity: a direct or indirect communication channel is needed to exchange data between the LO and PO.

- Promptness: the exchange of data should be timely in such a way that the delay of elaboration and communication of the new PO's state is negligible with respect to the application goals.

- Association: the connection between LO and PO can be uni-directional or bi-directional, as stated before. A bi-directional one is preferable to get the maximum advantages.

Augmentation   This means that the logical object can augment the capabilities of the PO by increasing its functions and features; this can be achieved by exposing APIs that facilitate the management of the PO. A physical object is limited and constrained, most of the time, with well-defined functionalities that remains for the entire life cycle of the object. The LO, instead, can be updated over time implementing new features, that is actually augmenting its physical object.

Composability   This refers to the ability to group logical objects into a single composed one, in order to centralize management and control; the single LO is increasingly more powerful because it represents a single PO, but it's important to be able to control and observe the behavior of composed objects as well as the individual components when required.

Memorization and Predictability   The LO's ability to store past and present data for future analysis, describing not only the current state of the physical object, but also its past life and past behavior. It is important to store and collect as much as possible data to extract the full potential in the future, even for simulations or predictions of the physical object's behavior during specific period of time or for future analysis, thanks to evolved AI technologies.

Replication   This refers to the fact that it is possible to have multiple replicas of a physical asset using different LOs in the virtual space or different environments; a PO can be replicated and virtualized multiple times in the virtual space, with each logical object reflecting the original physical one, even modelling different set of attributes and information. Over time, all these replicas should be consistent between each other.

Persistency   A logical object, when created, is understood to have a long life cycle and be available for a long period of time and should be persistent over its life cycle. It

should be resilient and persistent and always available to compensate the physical object limitation of its functions over time.

Accountability/Manageability   A logical object must be able to detect damage and problems of the physical asset and vice versa, it's the ability to fully manage all the expected and unexpected situations from the logical object to the pysical one and vice versa.

1.3.1   Shadowing and lifecycle of a Digital Twin

Shadowing refers to the mechanisms through which physical system data is captured, processed, and integrated into the Digital Twin, enabling seamless alignment between physical and digital entities, a synchronization of the two states: the so called mirroring. This mechanism reflects real-time the physical asset's state into the Digital Twin through various steps, from the low level data acquisition from sensors up to its manipulation, transformation, communication and final integration into the virtual asset. By this way, Digital Twins can be described in terms of properties, that are mapped one-to-one to physical properties of the physical asset, but not only that: we can add behavioral concepts such as actions or events and link information, like relationships. We can see how the shadowing process works inside the lifecycle of a Digital Twin in the image fig. 1.4. The DT starts entering in a *Not Bound* situation, with no associa-
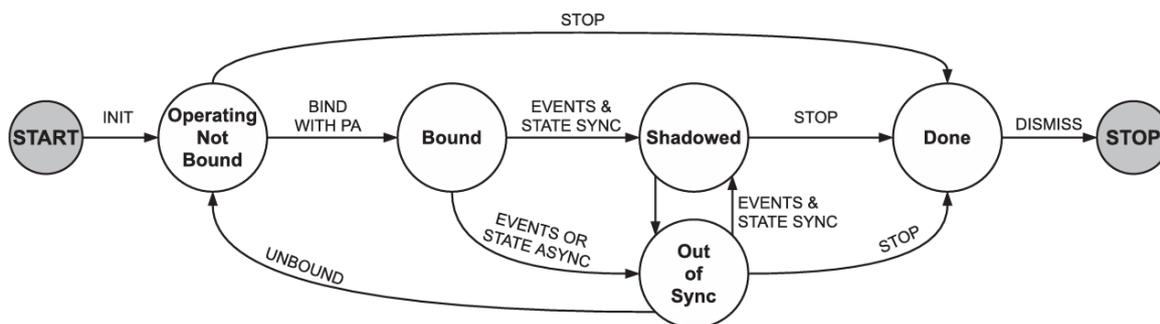
Figure 1.4: Abstract representation of the shadowing process and DT lifecycle

tion with physical entity and physical adapters to connect with. After being bounded with at least an adapter to communicate with its PO it enters into the *Bound* state: here we have the shadowing process, that is the continuous synchronization of properties

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and events between the two digital and physical parts, synchronizing every time the DT goes to an unexpected async situation. This show the application of the entanglement, representativness and reflection properties for example. The lifecycle of a Digital Twin spans the entire lifecycle of the physical system it represents, from early design phases to realise and operation until dismission. The Digital Twin evolves continuously, adapting its structure, models, and data as the physical asset progresses through different lifecycle phases. Lifecycle considerations address how the Digital Twin evolves across different phases, including design, operation, maintenance, and dismission, ensuring continuity, traceability, and adaptability of models, properties and data, behaviors over time. Another interesting formalization of the Digital Twins lifecycle describes different levels of sophistication, i.e. how many and what functionalities it offer [8] (table 1.1):

- Pre-Digital Twin: this refers to a prototype created before the physical object is build, supporting decision-making at design phase with a low fidelity model. Its goals are to validate key system concepts and decisions, mitigate all technical risks, and uncover problems early in the design process.

- Digital Twin: this virtual system now refers to a physical asset and models physical properties, receiving batch updates from the physical asset to update the virtual model representation with bi-directional interaction. This opens various opportunities, for example track the current state and explore the behavior of the physical asset under specific scenarios.

- Adaptive Digital Twin: this improves the previous level with the ability to adapt to the user/operator preferences or priorities using adaptive user interfaces between the physical and digital twins. The key point is the learning capability in different contexts using supervised machine learning algorithms.

- Intelligent Digital Twin: this includes enhanced Adaptive DT capabilities with unsupervised machine learning and reinforcement learning capabilities, giving the system a high level of autonomy over its environment.

1.3.2 Interoperable DT with Adapters

Interoperability is a critical point for the effective deployment of Digital Twins and achieving the application goals, as they must continuously interact with heterogeneous

Level	Model Sophistication	Physical Twin	Data Acquisition from Physical Twin	Machine Learning (Operator Preferences)	Machine Learning (System / Env.)
1 Pre-Digital Twin	Virtual system model with emphasis on technology / technical-risk mitigation	Does not exist	Not applicable	No	No
2 Digital Twin	Virtual system model of the physical twin	Exists	Performance, health status, maintenance; batch updates	No	No
3 Adaptive Digital Twin	Virtual system model of the physical twin with adaptive UI	Exists	Performance, health status, maintenance; real-time updates	Yes	No
4 Intelligent Digital Twin	Virtual system model of the physical twin with adaptive UI and reinforcement learning	Exists	Performance, health status, maintenance, environment; both batch/real-time updates	Yes	Yes

Table 1.1: Classification of Digital Twin maturity levels.

physical assets and digital systems across organizational and technological boundaries. For example, a single Digital Twin Prototype can be deployed across two different Digital Twin Instances, each referencing its own physical asset of the same type, but built with different technologies and communication channels [9].

To achieve this, Digital Twin architectures typically rely on dedicated adapters that mediate communication between the twin core, the physical asset, and external digital applications (fig. 1.5). Physical level adapters handle protocol translation, data normalization, and semantic alignment of sensor and check the correctness of data originating from the physical system. Application-side adapters, instead, expose standardized interfaces that allow analytics tools, real-time notifications, Rest APIs and decision-support systems to access and interact with the Digital Twin. By decoupling the Digital Twin logic from specific technologies and data formats enhances scalability, extensibility, and long-term maintainability of Digital Twin implementations.
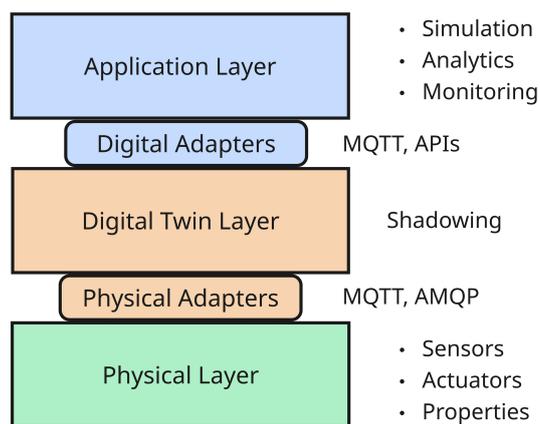
Figure 1.5: Example of a basic 3 layer DT based architecture

Interoperability is achieved exploiting all the standard technologies and interfaces available, for example the adoption of Semantic Web technologies and the Web of Things (WoT) Thing Description [10]: using shared ontologies and semantic annotations of properties and services, Digital Twins can achieve a common understanding of data, capabilities, and interactions. In this context, WoT Thing Descriptions can provide a standardized and semantic interface that enables heterogeneous physical assets and digital services, like Digital Twins, to be discovered, integrated, and orchestrated in an interoperable and technology-agnostic way.

1.4 Ecosystems of Digital Twins

Digital Twins operate within a complex and multi-layered technological environment that spans from the physical assets, where the sensing capability lies, to cloud-based platforms and digital application services. This environment can include heterogeneous components, including sensors and actuators, IoT devices, communication networks, edge and cloud computing resources, as well as data management and analytics platforms. The effective integration of these layers is essential to ensure reliable data acquisition, synchronization and easy management of Digital Twins.

1.4.1 From WoT to WoDT

Because of the wide range of applicability of Digital Twins and the big diversity of all the enabling technologies on the market, there is a risk of loss of uniformity resulting to a proliferation of vertical and closed silos of DTs. The evolution from the *Web of Things* paradigm to a *Web of Digital Twins* represents a shift from exposing connected physical assets as web-accessible entities to enable discoverable, dynamic, and semantically defined digital representations of these physical assets. A Web of Digital Twins can be imagined as an open and distributed ecosystem of connected DTs, as an interoperable service-oriented middleware for applications or Multi Agent Systems (fig. 1.6) [11]. While WoT focuses on interoperability at the device and service level (through standard-
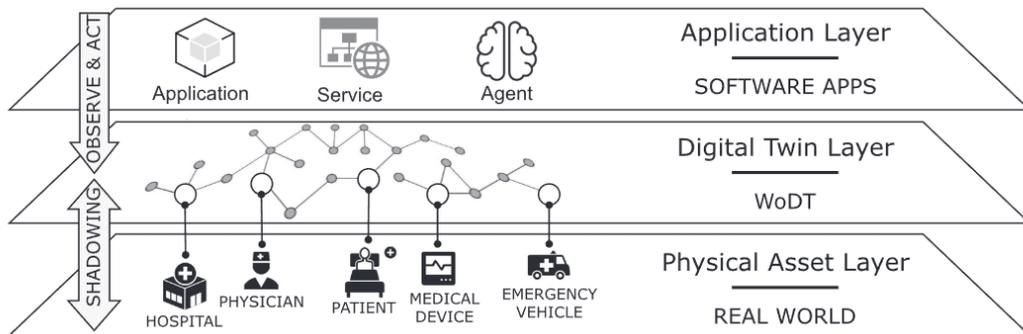
Figure 1.6: The WoDT layered abstract architecture

ized interfaces and machine-readable descriptions) the Web of Digital Twins extends this concept by encapsulating state, behavior, models, and lifecycle knowledge within Digital

Twins representation. In this paradigm, Digital Twins become first-class web entities that can be discovered, composed, orchestrated and queried, defining a cross-application distributed layer between the real world and the digital applications.

1.4.2   Hypermedia-based WoDT

The *Hypermedia-based Web of Digital Twins* extends the WoDT by leveraging Web standards, REST principles, semantic web and uniform interfaces to ensure openness and interoperability among heterogeneous Digital Twins across domains and organizations. By abstracting technological heterogeneity behind standardized Web interfaces, HWoDT enables discoverable and composable Digital Twin ecosystems that support different kinds of applications. A HWoDT Platform is introduced to manage these ecosystems, register Digital Twins, merge their data, allocate and orchestrate them and provide contextualized views and services at the application layer. Multiple platforms may coexist and share Digital Twins to support different perspectives and application needs [12].

1.5   Digital Twin Application Domains

We have seen the aerospace application field, but also in the context of Industry 4.0 Digital Twins are a key technology to enable cyber-physical systems, supporting real-time monitoring, optimization, and autonomous decision-making across the industrial processes, affecting the design, production and maintenance of products, and where a Hypermedia-based WoDT could represent a game changer technology to manage the ecosystem's complexity.

Manufacturing

Digital Twin applied in the industrial and manufacturing sector enables the simulation, optimization, and visualization of production systems, covering both manufacturing and logistical aspects, from individual components to the complete assembly fig. 1.7. Its primary objective is to enhance competitiveness, productivity, and efficiency by supporting key production system disciplines [13]:

- Planning and control: Digital Twins improve order planning through statistical assumptions, provide advanced decision support via detailed diagnostics, and enable

automated planning and execution.

- Maintenance: they support condition monitoring, predictive and anticipatory maintenance, impact analysis of system state changes, and data-driven evaluation of machine health using descriptive methods and machine learning across the machine lifecycle.

- Layout planning: Digital Twins enable continuous evaluation and reconfiguration of production systems through automated and application-independent data acquisition.
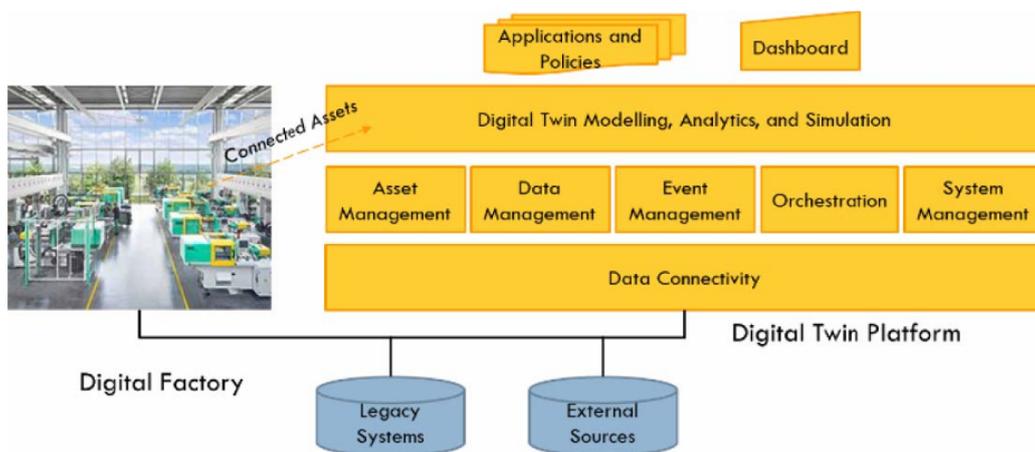
Figure 1.7: Example of an industrial architecture

Smart city and smart mobility

Digital Twins are increasingly recognized as a foundational technology for smart cities and smart mobility, enabling comprehensive digital representations of urban environments that integrate real-time data from sensors, connected vehicles, infrastructure, and citizen services, especially when combined with other technologies such as cloud-computing, IoT and Big Data. Digital Twins create virtual models of the physical mobility network and the transportation system, allowing cities to be aware of the urban congestion, accessibility, new sustainable transport systems and supporting a new era of autonomous driving.

Healthcare

Similarly, in healthcare applications, Digital Twins rely on interconnected sensing technologies, secure communication, and cloud-based processing to model patients, medical devices, or clinical processes, while addressing domain-specific requirements such as data privacy, reliability, and real-time awareness of surgeries, patient health or medical equipments.

1.5.1 Digital Twins and Digital Healthcare

Beyond individual Digital Twin instances, many real-world applications require the coordinated interaction of multiple Digital Twins within a shared environment, giving rise to a Digital Twin ecosystem. In hospital context, and particularly within surgical departments, such ecosystems include virtual representations of medical devices, operating rooms, clinical workflows, patients and medical staff, enabling a holistic representation of the surgical environment and supporting real-time awareness of what is happening, resource coordination, and planning optimization [14].

Related works

HospiT'Win and TraumaTracker

Digital Twin paradigm can lead to a wide range of applications, such as the virtualization and monitoring of all the hospital processes, physical assets (patients, equipments, locations, staff), surgeries execution and support, activity planning or emergency management. TraumaTracker focuses on real-time tracking of people or objects in indoor environments where GPS-based location is ineffective, supporting the medical team throughout the entire lifecycle of an emergency. The thesis investigates the use of BLE beacons as a reference infrastructure for position estimation inside a building, through mobile devices or wearable tags. Beacons periodically transmit low-energy signals that are received by mobile devices, which estimate position using Received Signal Strength Indicator (RSSI) based techniques, analyzing the principles, architecture, and performance of beacon-based indoor positioning systems, with particular attention to accuracy and robustness in complex indoor environments. Within the Trauma Tracker use case, this technology is applied to track healthcare staff, patients, or medical equipment

inside hospital facilities or other critical indoor settings, aiming to improve operational efficiency and logistic, situational awareness, and safety [15]. The HospiT'win project, similarly, focuses on building hospital Digital Twins by integrating real-time data from medical devices, staff, and patients to simulate and monitor hospital operations. It enables workflow optimization, predictive analysis, and scenario testing, allowing administrators and clinicians to assess the impact of changes in staff management, patient flow, or equipment allocation in a virtual environment before applying them in reality [16].

Personalized medicine

The Swedish Digital Twin Consortium (SDTC) is a multidisciplinary initiative involving academic institutions, healthcare providers, and industry partners aimed at applying Digital Twin technology to personalized medicine. The core objective of SDTC is to construct computational patient models with Digital Twins that integrate molecular, phenotypic, and environmental factors relevant to individual disease mechanisms. These high-resolution models allow researchers to simulate and evaluate the effects of thousands of potential drug treatments, identifying optimal therapeutic strategies for specific patients based on their unique biological profiles. This leads to a patient-centric vision, allowing clinicians to simulate various therapeutic interventions and predict their outcomes before they are administered to the actual patient [17].

Digital Twin Paradigm in Diabetes Prediction and Management

The paper reviews the emerging role of Digital Twin technology in diabetes care. Traditional diabetes care often responds to adverse glycemic events rather than anticipating them: Digital Twins, by contrast, create virtual replicas of patients through real-time data integration and computational modeling, enabling continuous monitoring and prediction of disease trajectories [18]. They identify key applications for Digital Twins:

- Glucose level prediction using continuous glucose monitoring and data-driven models.

- Personalized insulin dosing through adaptive modeling.

- Personalized insulin dosing through adaptive modeling.

- Dietary and lifestyle optimization informed by sensor data and simulations.

- Risk assessment for diabetes-related complications leveraging longitudinal patient data.

Computer Simulation in Operating Room Management

The paper explores the application of computer simulation techniques to the management of operating rooms (ORs) with the goal of improving process design and operational performance in large hospital settings. Operating rooms represent a high-cost and high-revenue service centers of hospitals, thus it is important to optimize the efficiency and effectiveness of the entire surgery department: most strategies relies on the improvement of perioperative process, that starts when the surgery decision is made (preoperative phase) until the convalescence and patient discharge (postoperative phase) [19], that can consist of manly five suprocesses [20]:

- Transport and admission to OR suite

- Diagnostic analysis, enter the induction room

- Enter the OR and execution of surgery

- Detachment of devices, wake up and monitoring

- Return to the ward area for post surgery care, follow-up

Simulation provides structural environment to understand, analyze, design and experimentally execute processes and then evaluate the outcomes in a quantitatively manner, enabling stakeholders to understand process variations, predict performance impacts, and make decisions. Importantly, the paper proposes the integration of simulation methods into the operating room management lifecycle as a tool for continuous improvement. [21].

Chapter 2

Case study: a Digital Twin ecosystem for monitoring and KPI analysis in a surgical department

As discussed in the first chapter, Digital Twins can bring multiple benefits in various fields, one of them is the healthcare sector, in which we find great enthusiasm in literature and related research projects. In this thesis, the focus is placed on the hospital environment, with particular attention to the operating room domain and its management. Operating rooms represent one of the most complex, resource-intensive, and critical areas within healthcare facilities, where efficiency, coordination, and decision-making have a direct impact on both clinical outcomes and operational performance. To address these challenges, this work investigates the adoption of a Digital Twin-based ORMS (Operating Room Management System) and also focuses on the development of a virtual simulation that faithfully reproduces the dynamics of the surgical department, modeling patient flows, resource usage, and process interactions as realistically as possible, supporting the validation of the Digital Twins system.

2.1   Operations Management in Hospitals

Operations Management in hospital is defined as the set of procedures, tools and roles that oversee the functioning of characteristic processes, through the adequate man-

agement of auxiliary and supporting services and activities, both healthcare and non-healthcare. In surgical departments the characteristic processes refer to the systematic planning, coordination, control of resources and processes involved in the delivery of surgical care and surgery execution. In this context, it focuses on optimizing the use of operating rooms, medical staff, equipment and supporting services across the perioperative process, from patient admission to postoperative recovery. Effective operations management aims to improve efficiency, reduce delays and costs, and enhance patient safety and quality of care [22]. Simplifying the theory a bit, operations management in the healthcare sector essentially involves two areas:

- Patient logistic: patient logistic aims to optimize the management of patient flows within the hospital, from the moment of first admission to the final discharge phase.

- Material logistic: the logistic of materials aims to ensure an efficient, appropriate and timely flow of all necessary resources to care processes, involving centralized warehouse and in-loco stocks.

To support all these actions in the surgery department, what is now called Operating Room Management (ORM) is needed, that are the procedures and tools related to planning and analyzing the surgical workflow [23].

2.1.1 Strategic ORM

The strategic level of an Operating Room Management System focuses on long-term and mid-term planning decisions that define how surgical resources are structured and allocated over time. Its main goal is to ensure that the operating suite is designed and organized to meet expected demand while balancing efficiency, cost, and quality of care [23]. Typical responsibilities include:

- Capacity planning, such as determining the number of operating rooms, available time blocks, and staffing levels.

- Operating room block scheduling, assigning OR time to surgical specialities or analysis of historical demand and strategic priorities.

- Workforce planning, including long-term allocation of surgeons, anesthesiologists, and nursing staff.

- Policy definition and performance targets, such as utilization rates, throughput objectives, and access time analysis.

- Evaluation of alternative organizational scenarios through simulation or analytical models to support strategic decision-making.

2.1.2 Operational ORM

The operational level of an Operating Room Management System addresses short-term execution and real-time control of surgical activities. It focuses on managing daily operations and responding to variability, disruptions, and unexpected events [23]. Typical responsibilities include:

- Daily surgery scheduling and sequencing, assigning specific patients to operating rooms and time slots.

- Real-time coordination of surgical workflows, including patient preparation, room setup, and turnover activities.

- Monitoring operating room status, such as surgery progress, delays, cancellations, and overruns.

- Dynamic resource allocation, reassigning staff, rooms, or equipment in response to emergencies or deviations from the plan.

- Decision support for operational adjustments, including rescheduling, prioritization of urgent cases, and conflict resolution.

Production Planning

Surgeries must be planned using daily operating notes to ensure compliance with the necessary recovery and disinfection times for operating rooms, using the historical database of collected data to forecast operating room occupancy. Defining variables and constraints to consider is essential to develop an adequate schedule without creating conflicts. In terms of surgical scheduling, the weekly surgical note must be prepared with sufficient advance notice to ensure the activation of the patient telephone screening process. The daily surgical note can then be finalized: it contains the names of patients who

are candidates for surgery on a specific day and who have confirmed their availability for that date, based on the results of the telephone screening and pre-admission assessment [22].

2.2 The surgical department

The surgical department is a highly specialized and regulated area of the hospital, designed to support surgical activities while ensuring patient safety, clinical efficiency, and strict infection control. It is composed of multiple interconnected spaces, each serving a specific role within the perioperative process and organized according to functional, logistical, and hygienic principles.

These spaces typically include operating rooms, pre-operative and induction areas, postoperative recovery units, and inpatient wards, which together enable the seamless progression of patients and staff throughout the surgical pathway.

2.2.1 Different areas and compartmentalization

The operating block must be divided into progressively less contaminated areas, from the entrance to the operating rooms. The layout of the operating block is further characterized by the separation of areas with different levels of microbial contamination risk, commonly classified as contaminated, clean, and low-microbial-load zones, as we can see the example of the surgical department of Cervesi Hospital (fig. 2.1). This spatial organization is essential to prevent cross-contamination, regulate the movement of people and materials, and maintain sterile conditions during surgical procedures. Understanding the structure and functional relationships among these areas is fundamental for analyzing operating room workflows [24]. In accordance with these provisions, the operating room complex has separate internal routes for "dirty" and "clean" areas. Everything is designed to prevent bacterial contamination, such as the operating room entrance and exit doors, which are equipped with no-touch opening systems. These information are fundamental to better understand the surgical department's dynamics and realize a specific detailed simulation [26].

Figure 2.1: Planimetry of the Cervesi Hospital [25]

2.2.2 Operating Room

The operating room is the environment where surgery is performed, which houses a multitude of specialized equipment and instruments to assist the medical team. The core of the operating block is represented by the operating rooms, which are equipped with advanced surgical, anesthetic and monitoring technologies and are designed to ensure sterility and patient safety. These rooms are supported by a set of auxiliary spaces, including preoperative rooms for patient preparation, anesthesia induction rooms, postoperative recovery units and dedicated storage and sterilization areas for surgical instruments and materials. The presence of the following elements in operating rooms can be considered essential [24]:

- Operating table technologically suited to the different types of surgical procedures complete with accessories.

- Vital signs monitor capable of analyzing the main patient parameters, from ECG to capnometry, from invasive and non-invasive blood pressure, to oximetry and plethysmography.

- Surgical lamps, defibrillator, electrical scalpel and many other high-precision and fundamental instruments.

Pre-operation and post-operation rooms

In the pre-operation room (or preparation room), patients arriving from the inpatient wards are greeted by the operating room staff and remain there until transferred to the operating room. During the waiting period, the patient undergoes further preparation protocols for the procedure, including a final pre-operative assessment by healthcare professionals fig. 2.2. Separated, but connected to the operating room, there are also spaces reserved for the team to prepare the skin before surgery: in this area, operating room staff (instrumentalists and surgeons) prepare to perform the surgical scrub necessary to reduce the microbial flora of the hands and forearms [24].
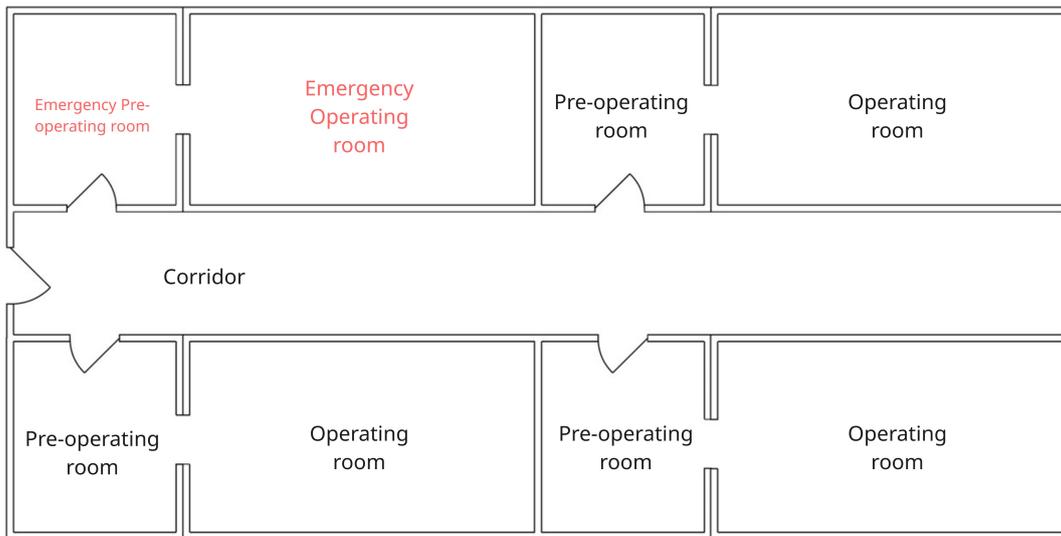
Figure 2.2: Example of surgical department structure

The recovery room is the facility within the operating department where doctors and nurses perform post-operative care functions, such as monitoring vital signs and functions, administering medications and infusion therapy, monitoring the patient's state of consciousness, and performing a comprehensive clinical assessment of the newly operated patient before returning to the inpatient ward, where they will continue their clinical journey [27].

2.3   Peri-operative journey

The peri-operative journey of a programmed surgical patient represents the best practicable pathway within the hospital, the surgery department and concerning the medical staff. The patient's perioperative journey begins at the moment of inclusion on the waiting list and ends at the time of discharge. All the actions included in this period must be governed, as they are connected to the patient's journey. This is strongly related to time (fig. 2.3):

- Waiting time for recovery (waiting list)

- Amount of time necessary for the pre-recovery activities to prepare the surgery procedure

- Total time of the peri-operative process
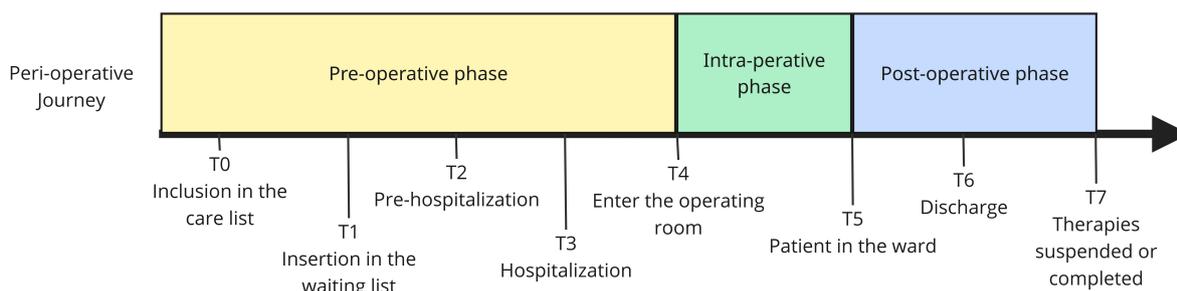
Figure 2.3: Patient's peri-operative journey

2.3.1   Waiting Lists

Surgical waiting lists represent the formal entry point of the patient into the perioperative pathway and play a crucial role in the organization and management of surgical care. They serve not only as a scheduling instrument, but also as a governance mechanism to ensure clinical adequacy, prioritization, and fair access to surgical procedures. An effective management of waiting lists directly influences downstream perioperative phases, impacting resource allocation, operating room utilization, patient safety and overall infrastructure performance [28]. Referring to AUSL Emilia Romagna and italian

SSN (Servizio Sanitario Nazionale), the indication for scheduled hospitalization can be made by a doctor employed by or contracted with the SSN.

- Taking charge phase: it's the moment when the patient is assessed by the facility which will follow the entire clinical and care processes of the patient, until the intervention is performed. The booking date (insertion in the waiting list) corresponds to the moment in which the patient is actually fit to undergo surgery, having already done all the diagnostic tests necessary for a correct diagnosis and to define the therapeutic directives.

- Waiting list phase: from the date of registration on the list until the day of hospitalization (date of admission), the waiting time will be calculated.

- Pre-recovery phase: the preoperative phase begins, based on the expected period of hospitalization, with the patient's pre-admission call. Its main purpose is to assess the patient condition to avoid any risk and optimally manage the peri-operative course.

Access policy

Access to scheduled inpatient surgical procedures is governed by a combination of clinical priority, chronological order of insertion and required resources. Patients are assigned to a priority class at the time of inclusion in the waiting list, based on standardized clinical criteria defined at national level and further refined through regional analysis. Although an initial or default priority class may be suggested for each pathology, the doctor can modify it according to the patient's specific clinical condition, including disease severity, risk of deterioration, presence of pain or functional impairment, and special time-dependent clinical needs. Priority classes are dynamic and can be updated if the patient's condition changes. Four clinical priority classes are defined, each associated with a maximum waiting time (table 2.1).

To ensure fairness and efficiency in calling patients from the waiting list, a scoring-based ordering mechanism is proposed using the following mathematical formula.

$$Score_i = \frac{Maximum\ time\ expected\ from\ the\ least\ urgent\ priority\ class}{Maximum\ time\ expected\ by\ priority\ class_i}$$

Table 2.1: Clinical Priority Classes for Scheduled Surgical Admissions [28]

Priority Code	Description
A	Admission within 30 days for clinical cases that may rapidly worsen, potentially becoming emergencies or causing severe harm to prognosis.
B	Admission within 60 days for cases with intense pain, severe dysfunction, or disability, without rapid deterioration or immediate prognostic risk.
C	Admission within 180 days for cases with minimal pain, dysfunction, or disability, and no tendency to worsen or significantly affect prognosis.
D	Admission without a defined maximum waiting time for cases that do not cause pain, dysfunction, or disability. These cases must still be performed within 12 months.

This score combines the time already spent on the waiting list with a severity coefficient derived from the assigned priority class. As a result, patients progress through the list at different speeds depending on both urgency and waiting time, preventing lower-priority patients from being indefinitely postponed while still preserving clinical prioritization, promoting fair access and efficient management of surgical waiting lists.

Maintenance of the waiting list

Waiting lists must be periodically reviewed to ensure the accuracy of patients status and position, allowing corrections to optimize surgical scheduling. If a patient's priority level changes, the total waiting time is still calculated from the initial registration date. Patients can be temporarily suspended from the list due to medical contraindications or personal unavailability. During suspension, their priority score is preserved, the suspension period is documented, and the waiting time counter is paused. If a patient fails to attend two consecutive reassessment visits, they are removed from the list. Patients exit the waiting list when surgery is performed, postponed, or cancelled [28].

2.3.2 Intra-operative phase

The intraoperative phase involves managing the activities performed by the surgical team for the patient from the moment they enter the surgery department until they leave. This

phase includes the surgical procedure, the central event of the entire process (fig. 2.4). Proper planning, scheduling, and organization of activities maximizes the safety of patients and healthcare professionals, including through the proper use of control tools placed throughout the process (operating room checklist).

| Patient Appointment | Surgery Scheduling | Patient is hospitalized | Operating Room | Returning to ward | Patient discharge |
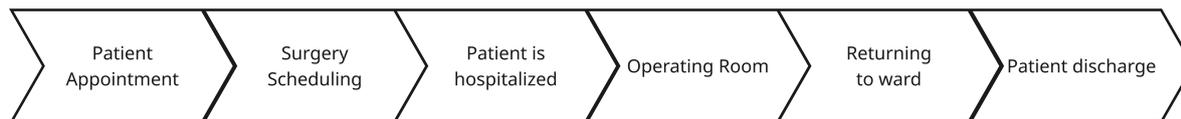
Figure 2.4: Surgery lifecycle

Risks related to operating rooms

During the intra-operative phase, operating rooms are inherently high-risk environments due to the complexity of surgical procedures, the involvement of multiple professionals, and the critical nature of clinical decisions. Unsafe surgical care contributes significantly to adverse outcomes: surgical complications occur in an estimated 25 % of patients undergoing inpatient operations, and postoperative mortality can range from 0.5 % to 5 %, with a large proportion of adverse events in hospitalized patients being related to surgical care. These risks arise from procedural errors, miscommunication among team members, incorrect identification of patients or surgical sites, equipment failures, and lapses in standard safety practices. The dynamic and modular nature of modern surgical workflows increases the risk of information loss and errors when care is fragmented among different professionals. Improving adherence to safety protocols and standardising perioperative procedures are therefore critical to reducing preventable harm in the operating room setting ([29]). To mitigate the risks inherent in surgical care, international and national bodies have promoted the use of Surgical Safety Checklists (SSCL) based on the World Health Organization's Safe Surgery Saves Lives program (fig. 2.5). These checklists provide structured checks at key moments in the perioperative workflow — before anesthesia induction (Sign In), before skin incision (Time Out), and before the patient leaves the operating room (Sign Out) — and involve the entire surgical team in verifying critical safety items. In Italy, the Ministry of Health has adopted and adapted the WHO checklist to the national context, resulting in a 20-item SSCL used

Figure 2.5: World Health Organization SSCL model

widely across hospital operating rooms to verify patient identity, surgical site and procedure, anesthesia safety, equipment function, and other critical elements. The SSCL is not intended to be exhaustive, but rather to standardise communication and reduce preventable complications; evidence suggests that incomplete or non-compliant use of checklists is associated with increased risk of surgical complications, underscoring their role as a key component of intraoperative safety and quality of care ([30]).

2.4 The needs of interoperability

Interoperability represents a fundamental requirement in healthcare environments, where heterogeneous systems, medical devices, and information platforms must seamlessly exchange and interpret data. In surgical departments, clinical workflows involve multiple actors, such as surgeon and medical staff, technologies, and software solutions. Without effective interoperability, information fragmentation can lead to inefficiencies and increased risks for patient safety: this is what enables the transition from isolated infor-

mation silos to a patient-centered care ecosystem.

In the context of this project, which aims to introduce a Digital Twin ecosystem within the surgical department, interoperability becomes even more critical: Digital Twins collect data from patients and hospital's physical assets that should be easily accessed by different institutions such as different hospitals, adopting standardized communication protocols and healthcare data standards.

To ensure that information is not only transmitted but also understood uniquely by different contexts, the adoption of global standards is essential.

2.4.1 Fast Healthcare Interoperability Resources

One of the most important standard nowadays is HL7 FHIR, that stands for *Fast Healthcare Interoperability Resource*, and is a standard for exchanging healthcare information between different institutions and systems in a electronic manner. FHIR breaks down healthcare information into small, modular, and manageable units called **resources**, such as Patient, Observation, Medication or Location, offering a standard framework that defines a common way to solve healthcare problems and the diversity of concepts and representations in the global healthcare world. Some usage scenarios are:

- **Personal Health Record** for electronic record systems (such as Fascicolo Sanitario Italiano), that provides a RESTful API for patients to access their medical information using common web interfaces or mobile applications.

- **Document Sharing**: support and integrate healthcare information from a variety of sources.

- **Decision support**: integrating healthcare information allows to create decision support software to help the medical staff to patient surveillance, procedures planning and so on.

This standard helps developers to achieve pre-defined levels of integration, that allows a step by step evolution from the basic framework specifications to the ability of reasoning and high level medications definitions (fig. 2.6).

FHIR is built around the concept of Resources, which are modular, reusable, and self-contained data structures representing specific healthcare concepts. Each resource
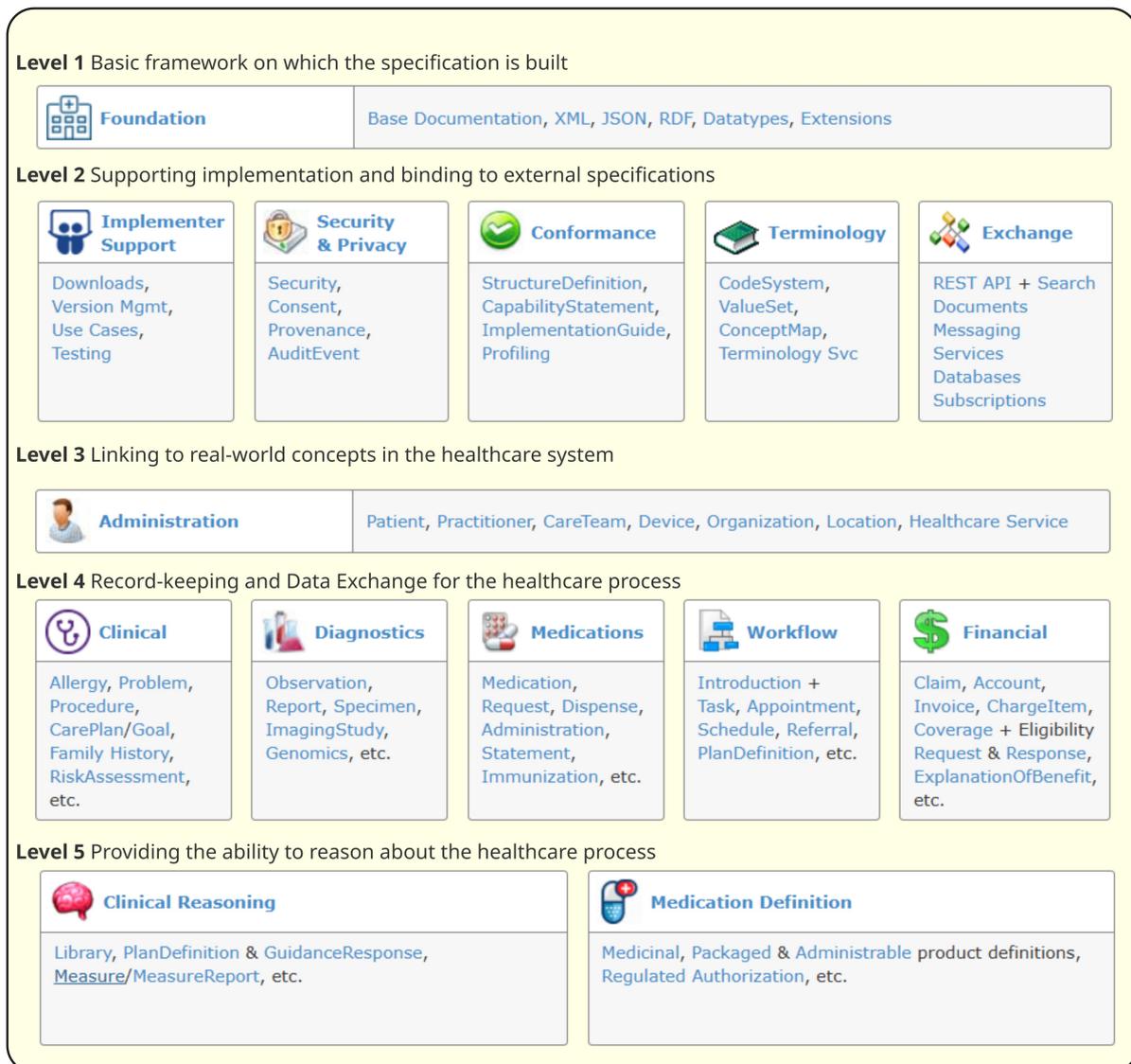
Figure 2.6: FHIR levels

defines a standardized set of attributes, identification data, both human and machine readable contents and code systems and defined relationships. Using FHIR resources we can also bind them with other standard frameworks to achieve maximum integration, for example *SNOMED CT* to model standard medical concepts, such as surgery types (fig. 2.7).

It utilizes common web technologies (HTTP, RESTful APIs, JSON/XML) to allow different healthcare systems to securely share, access, and interpret patient data, improv-
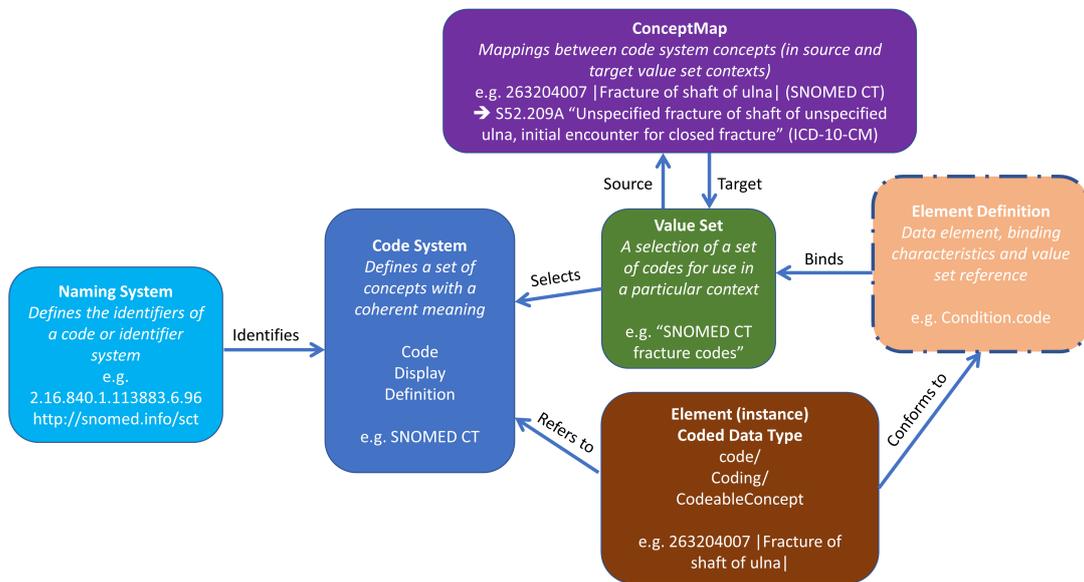
Figure 2.7: FHIR terminology

ing interoperability. One of them is the RDF representation serialized with the Turtle format, that is defined to assist the process of bridging between operational data exchange and a more semantic representation. By this way we are able to create a formal knowledge representation and a semantic layer over the healthcare resources, allowing a reasoner to navigate the knowledge by means of the FHIR ontology language.

2.4.2 SNOMED CT

As mentioned in the previous FHIR explanation, SNOMED CT, that stands for *Systematized Nomenclature of Medicine - Clinical Terms*, is not a simple vocabulary, but a complex, multi-hierarchical ontology based on descriptive logic, that aims to remove language barriers, enabling consistent clinical information recording and supporting record checking and sharing. In practice, SNOMED CT is used to encode diagnoses, procedures, findings, body structures, and clinical events in a standardized and machine-interpretable way. Its use ensures that clinical data recorded in different systems retain consistent meaning, supporting data aggregation, analytics and interoperability across institutions.

It is structured as a formal ontology composed of concepts, descriptions, and relationships. Each concept is identified by a unique numeric identifier and represents a

clinical meaning (e.g. Appendectomy or Postoperative wound infection). Descriptions provide human-readable terms associated with a concept, including a *Fully Specified Name* (FSN) and synonyms, while relationships define semantic associations between concepts. SNOMED CT is organized hierarchically using "is-a" relationships, forming a structure in which a concept may belong to multiple parent categories (fig. 2.8).
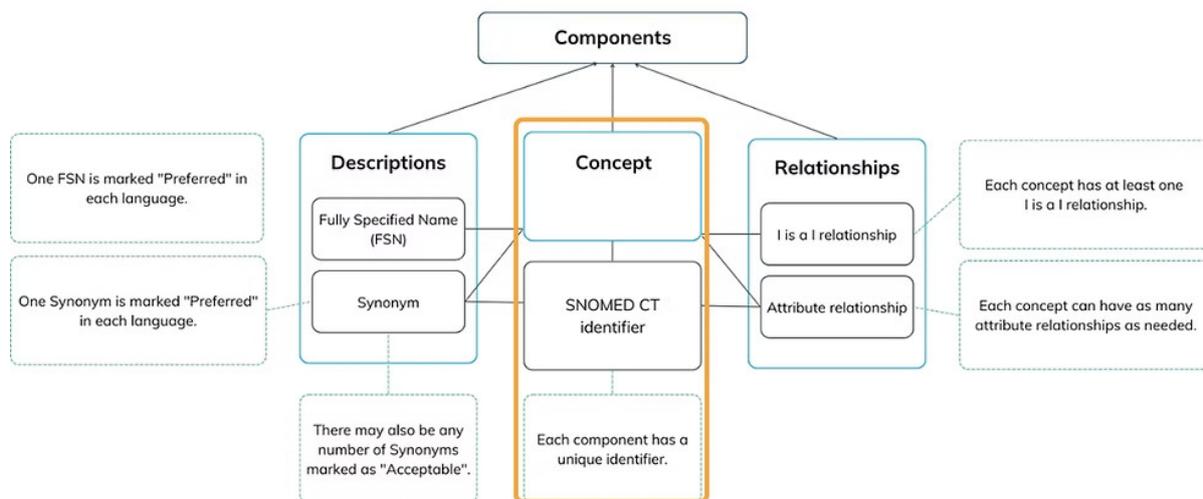
Figure 2.8: SNOMED CT components

Within the HL7 FHIR framework, SNOMED CT is used through terminology bindings with resources such as Condition, Procedure, Observation, and Encounter that includes coded elements represented using the CodeableConcept data type. These elements can be referenced to SNOMED CT codes to increase the descriptive potential, where FHIR provides the structural interoperability level, while SNOMED CT ensures semantic accuracy.

2.5 Benefits of a Digital Twin based OR management

The introduction of Digital Twins in healthcare, as we seen, represents a highly innovative step that has the potential to significantly transform the way healthcare services are organized and delivered. There is broad agreement that DTs can effectively support real-time monitoring, data collection and performance analysis, ultimately improving data-driven decision-making through analysis and optimization.

2.5.1 Goals and challenges

The primary goal is the virtualization of all relevant physical assets involved in the operating block, including operating rooms, surgeries, patients and vital signs monitor, enabling a coherent digital representation of their state and interactions. Building upon this foundation, the project seeks to develop an Operating Room Management system natively based on Digital Twins, capable of supporting data acquisition and KPIs elaboration. So, a further objective is to trace the patient's surgical pathway by exploiting real-time physiological data and event tracking throughout the peri-operative path, from admission to post-operative care. Finally, Digital Twins are leveraged to measure and analyze Key Performance Indicators of the surgical department, providing a structured tool to evaluate operational performance and support inefficiencies identification, continuous optimization of surgical workflows. These goals, however, are accompanied by significant challenges, including data interoperability across heterogeneous systems, real-time data integration and reliability and accurate modeling of the complex clinical processes and dynamics of a surgical department into a dedicated simulation.

2.5.2 Monitoring: a way to prevent and improve

Continuous and real-time monitoring of surgical patients and peri-operative events has the potential to become a game changer in surgical care, providing clinicians with timely insights that can improve outcomes and prevent complications. Digital twins can help medical staff gain a comprehensive view of all department processes, integrating policies such as SSCL, waiting list management and in-depth monitoring in order to create a

knowledge base for KPI measurement, that is the most powerful way to get awareness of the current situation and lead improvements in all critical areas. Studies have shown that continuous physiological monitoring systems can enhance the early detection of patient aggravation, enabling rapid clinical intervention and reducing adverse events such as desaturations and other vital sign abnormalities. This type of surveillance, particularly when combined with real-time alert systems, contributes to reduce complications and may improve post-operative recovery. The integration of smart IoT devices, wearable sensors, and digital monitoring platforms into surgical care enables more precise and individualized tracking of vital signs, instrument positioning, and recovery markers, leading to improved safety, shorter hospital stays, and more efficient use of healthcare resources (fig. 3.4).
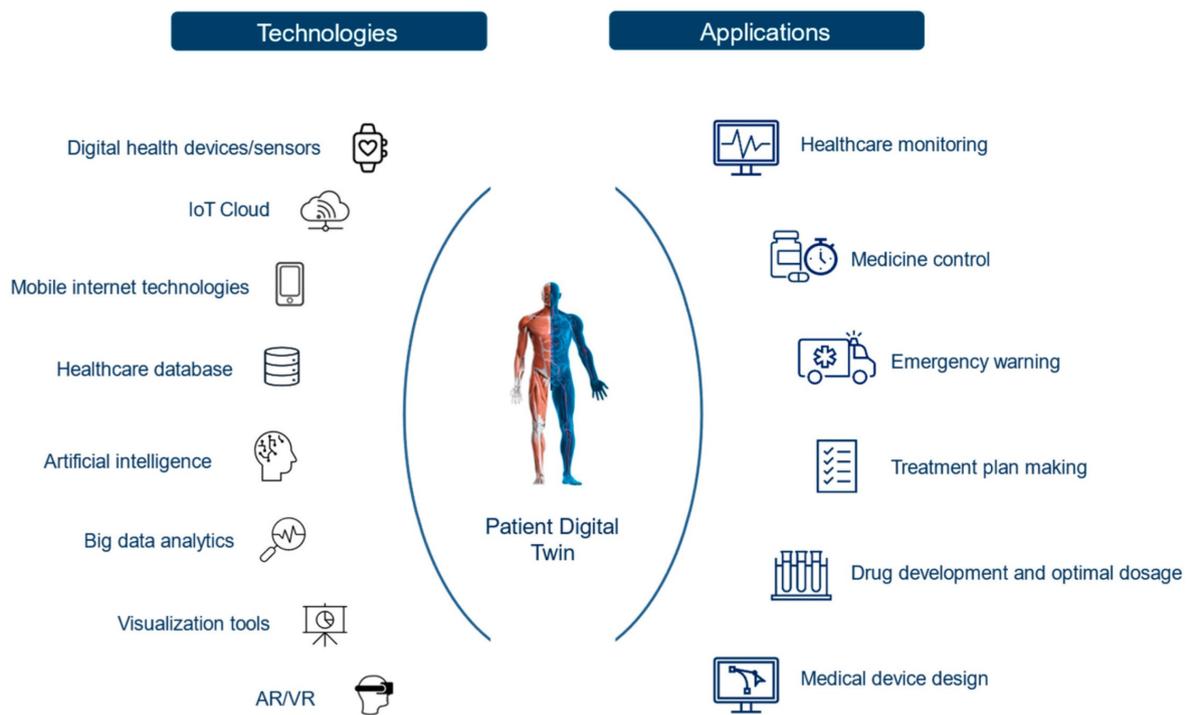
Figure 2.9: Examples of integrating technologies into DTs

2.5.3 Simulation of the environment

Simulation, as we said, plays a central role in validating the proposed Digital Twin ecosystem, as it enables the assessment of system behavior under realistic and controlled conditions before deployment in a real clinical environment. Through a collaboration with the AUSL Emilia-Romagna, a high-fidelity simulation has been developed to closely replicate the dynamics of a hospital operating block composed of multiple operating rooms and an inpatient ward. The simulation was designed to be coherent with the project objectives and to reproduce the entire perioperative pathway of a patient, from admission to discharge, by registering clinical events, operational actions, and workflow transitions. Key constraints, resource availability, and surgical team configurations were explicitly modeled to reflect real organizational and logistical conditions. By mirroring patient flows, staff interactions, and operational dependencies, the simulation provides a reliable virtual environment for testing, validating, and refining the Digital Twin–based ORM system.

Chapter 3

Problem and analysis

The first step in system design is understanding and analyzing the domain of interest. In our case study we need to understand the hospital context, more precisely the surgical department and all its intrinsic dynamics, regulations and processes. This project adopts a Domain-Driven Design approach to address the complexity of managing surgical department context, as the starting point do analyze and design a digitalized Operating Room Management System and a coherent digital model of the surgical department that accurately reflects real surgical processes, organizational structures, and operational constraints. Before defining use cases and user stories, the project followed a structured Knowledge Crunching phase for the strategic design, which is a fundamental activity in Domain-Driven Design. This phase aims to deeply understand the problem domain by collaboratively exploring the surgical environment together with domain experts.

3.1   Surgical department context

We mentioned, in previous chapter, that the surgical department is one of the most critical, expensive and valuable areas of a hospital from both the patient and stakeholders perspective, therefore an in-depth analysis of the surgical department is crucial to have a complete view of the processes and elements involved.

3.1.1 Structure of a surgical department

The surgical department can be composed by multiple specialized locations and, as we saw in the previous chapter, divided and compartmentalized into different areas, but the typical layout includes:

- Hospital ward: the entry point of a surgical journey for a patient, composed of multiple bedrooms that can be categorized with different levels of clinical severity for the patient (day surgery or monitored room).

- The filter area: defines a specific department area that physically separate two different compartment, dirty areas from sterile ones.

- The operating rooms: the locations where the surgeries are performed, which are the sterile area of the entire department. They can include a separated preparation room for induction and a post operation room for patient wake up and recovery.

- Tracking systems for patients and surgical events.

Urgency/Emergency surgery must also be considered, which is represented by surgical cases with urgency or even emergency characteristics. Usually a urgent surgery is the same thing of a ordinary one, but with high priority and tighter deadlines. Emergency surgeries, instead, are those interventions that are accessed through the Emergency Department (Pronto Soccorso) and are not planned, requiring a timely procedure management without registration and tracking needs. For urgent/emergency surgeries, the dedicated operating room must be used, if available; otherwise, the first available operating room must be identified.

3.1.2 Medical staff

Following a series of collaborative discussions with domain expert, we identified the key human actors involved in the perioperative process that are relevant to model the surgical department. These roles include:

- Patient, who represents the central subject of the surgical journey.

- Surgeon, responsible for performing the surgical procedure and making clinical decisions.

- Anesthesiologist, who manages anesthesia and monitors the patient's physiological conditions.

- Surgical assistant, who supports the surgeon during the intervention.

- Nurse, who coordinates perioperative care activities and ensures adherence to clinical protocols.

- Stretcher bearer, responsible for safely transporting the patient between hospital units.

Modeling these roles explicitly allows us to capture responsibilities, interactions, and constraints across the surgical workflow, ensuring that both clinical and organizational aspects are accurately represented within the digital twins and the simulation of the surgical department.

3.1.3 Operating rooms

In the surgical department context, operating rooms are represented as structured environments composed of multiple medical instruments and supporting systems. While several devices contribute to surgical activities, the modeling effort focuses on the key instrument that is essential for the project objectives: the vital signs monitor, which provides real-time tracking of various vital signs of the patient, such as heartrate and pulse oximeter. Each operating room is associated with a set of daily time slots that define its availability for surgical use, typically organized into a morning slot and an afternoon slot, during which surgeons can perform scheduled procedures. Additionally, we can have operating rooms that are available for only a specific type of surgery or similar type surgeries within a slot: this is obviously the best way to optimize utilization without preparing the OR for other totally different types of surgeries, ensuring greater safety for the patient procedure. Another important aspect of operating rooms utilization concerns the sanification processes, which are mandatory after the completion of each surgery. Sanification temporarily makes the operating room unavailable, representing a critical operational constraint that must be enforced to ensure patient safety, infection control, and compliance with clinical regulations.

3.1.4 Current situation

The current operating room management process is only partially digitalized and still heavily dependent on manual and paper-based tools. Surgical activities are coordinated through a printed daily schedule, a QR code scanning system, and a paper form assigned to each surgical procedure, which is manually filled in by the medical staff.

The QR code system is intended to track the most relevant phases of the perioperative pathway of a surgical procedure:

1. Patient exits the hospital ward

2. Patient enters the operating suite

3. Patient enters the OR (from now on if, for any unexpected reason, the surgical procedure is interrupted, step 8 is the next one)

4. Anesthesia is performed

5. Anesthesia is effective

6. Surgery is started

7. Surgery is completed

8. Patient is moved outside of the OR

9. Patient leaves the operating suite

10. Patient enters a hospital ward (which can be different from the one which he came from)

Although the QR code system records the execution of these steps, the timing of each phase is also manually annotated on the paper form. One of the main issues with the current approach is the frequent discrepancy between the time at which QR codes are scanned and the actual execution time of the corresponding activities. This misalignment occurs because medical staff are primarily focused on patient care and may forget or delay scanning during critical moments. As a result, staff often rely on the paper form to retrospectively adjust timestamps based on their recollection and to add supplementary information they consider relevant for documenting the surgery.

Another significant limitation of the current system is related to data availability and integration. The information collected through the QR scanning system is stored in hospital-specific local databases, preventing centralized or real-time access to the status of ongoing surgical procedures. This fragmentation limits the ability of coordinators to effectively manage operating room resources across multiple facilities, leading to inefficiencies in scheduling and utilization.

Discussions with medical staff highlighted several key pain points, including the poor readability of handwritten data, the limited space available on paper forms to record surgical steps, and the lack of reliability of recorded timestamps. Additionally, changes such as surgery delays or cancellations are not properly tracked due to the static nature of printed schedules. The absence of clear accountability in data collection further complicates process improvement efforts, while the lack of real-time visibility into operating room availability results in sub-optimal operational management [14].

3.1.5 Use case and user stories

The initial tool for domain analysis is the creation of use cases, shown in fig. 3.1, involving the actors defined in the previous section.

Acceptance and entry into hospital ward

Definition The surgical programmed patient must first check in to the acceptance desk and wait in the waiting room to be greeted by a nurse, who will accompany him or her to the hospital ward in preparation for the operation. When the programmed surgery is about to start, the stretcher bearer should notify the patient (fig. 3.2).

- Main roles: the patient to be operated and the nurse who will manage the recovery

- Action: the patient gets recovered

- Benefit: the patient is able to start its peri-operative journey

Condition of satisfaction The patient should be in the waiting list and its surgery already programmed.

Figure 3.1: Use cases
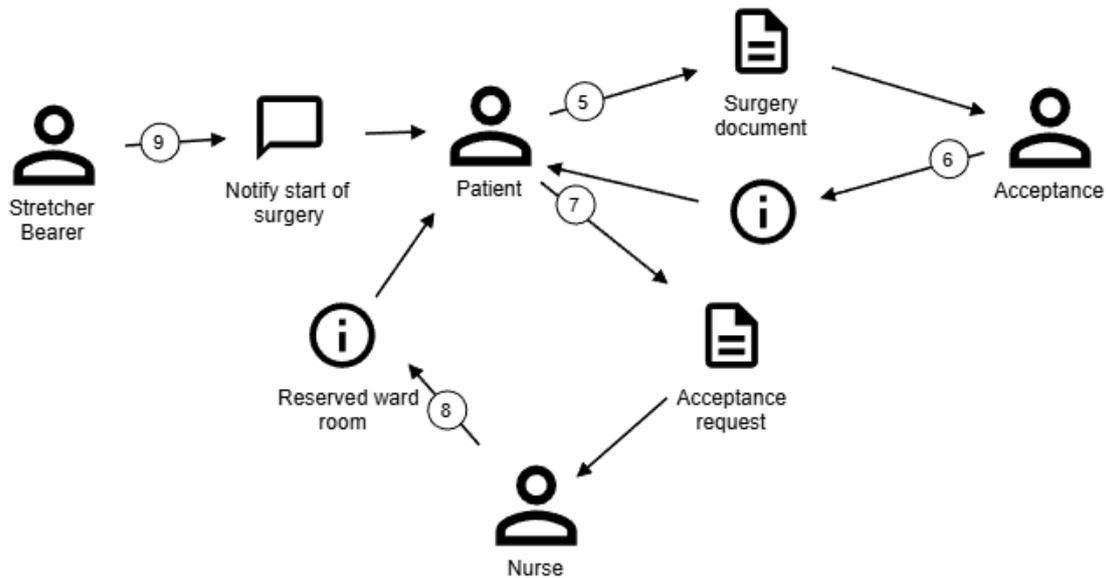
Figure 3.2: Patient admission user story

Start of the intra-operative phase

Definition   The surgical intervention needs a preliminary intra-operative phase, that starts with the stretcher bearer transferring the patient to the surgical staff inside the preparation room. Then the stretcher bearer return back to ward (fig. 3.3).

- Main roles: the stretcher bearer actor is the one who is responsible for the safe transport of the patient inside the surgical department, from the ward to the operating room and back.

- Action: the patient gets transferred into the operating block

- Benefit: the patient starts its peri-operative journey

Condition of satisfaction   It's time for the programmed patient to be operated, following the schedule of the day. The stretcher bearer, the operating room and the surgical staff should be ready.
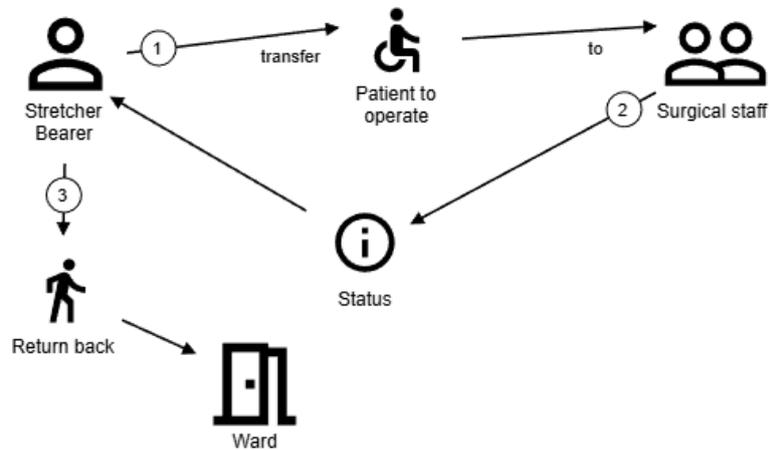
Figure 3.3: Start of the intra-operative phase

Surgery execution

Definition   The patient should do the induction of the anaesthetic before the surgical procedure starts. Then the intervention can be done with the incision and finally the suture on the patient to terminate the surgery.

- Main roles: surgical equipe and the patient

- Action: the surgical equipe performs the surgical procedure

- Benefit: the patient goes under surgery and terminate the most critical intra-operative phase

Condition of satisfaction   The patient must be ready for surgery and pass all the safety check list requirements.

Emergency without schedule

When modeling a simulation of a surgical department, it is necessary to consider the emergency case of an unplanned surgery with timely needs. The emergency usually comes from the Emergency Department and shortens the peri-operative process to its
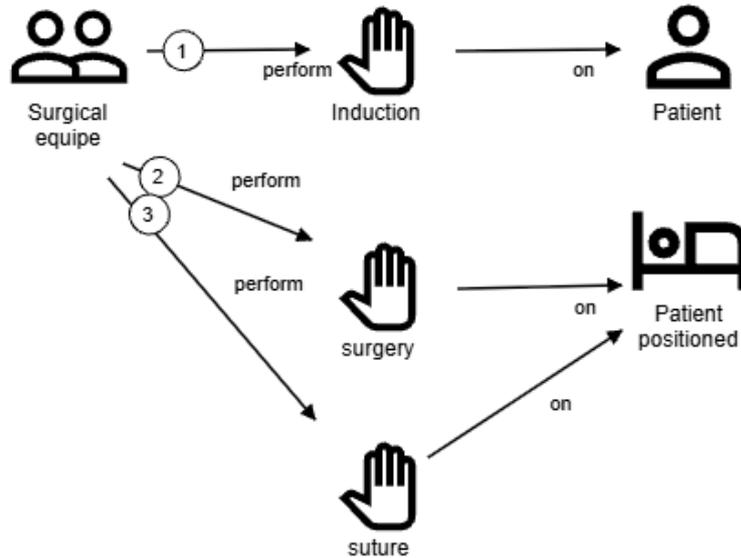
Figure 3.4: Surgery execution user story

crucial phases, that is the timely intervention, possibly in the emergency operating room or the first available one (fig. 3.5).

- Main roles: the emergency patient

- Action: the surgical equipe performs the emergency surgical procedure

- Benefit: the patient goes under surgery as fast as possible

Condition of satisfaction   Usually there are no condition of satisfaction when an unplanned emergency case comes in.

3.1.6   Activity diagrams

Based on what we have seen with domain expert and the user stories, more specific and detailed activity diagrams can be defined. We can see the acceptance of patients in fig. 3.6, involving the patient and the nurse of the surgical department. Next, we have the intra-operative phase, involving the patient and the surgical equipe, defining
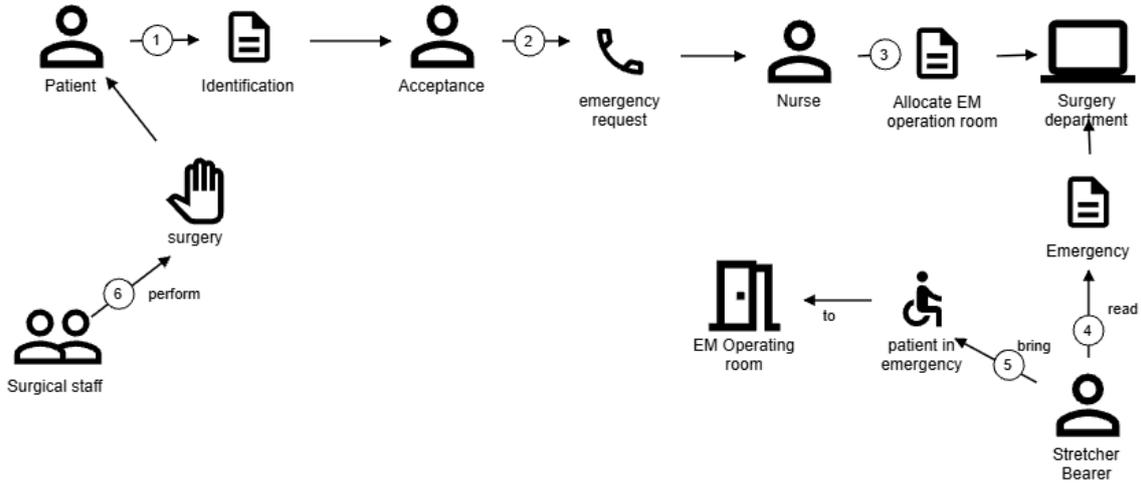
Figure 3.5: Emergency management user story

the complex flow of subsequent activities and collaboration mechanisms between the medical staff (fig. 3.7). Finally, we have the post-operative phase, that starts with the end of the surgical procedure and terminates with the discharge of the patient from the hospital (fig. 3.8).

3.1.7 Mapping the intra-operative journey

Process improvement begins through its measurement, that is, the identification of a series of chronological events in time capable of describing the flow of activities performed on the patient. This ultimately allows for objective understanding and the development of indicators that can describe the proper flow of process activities and the effectiveness and efficiency of surgical care. The patient surgery journey can be fully described with 15 fundamental events (table 3.1), which describe all the patients' position change and surgery steps. The events described do not necessarily need to be recorded, their recording depends on the type of path the patient undertakes, but their important to understand the surgery timings.
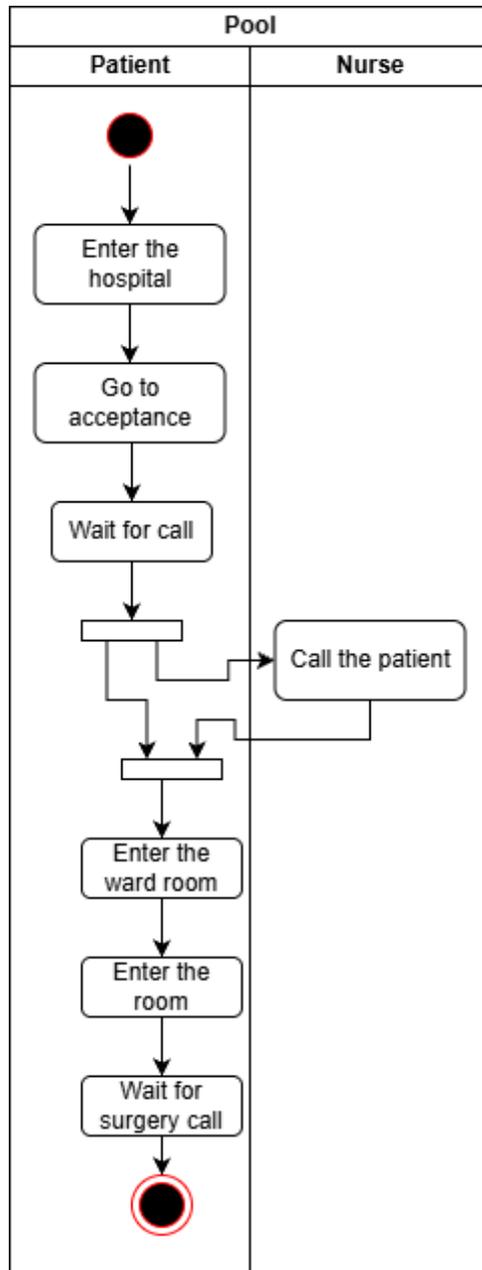
Figure 3.6: Activity diagram of check in for patients
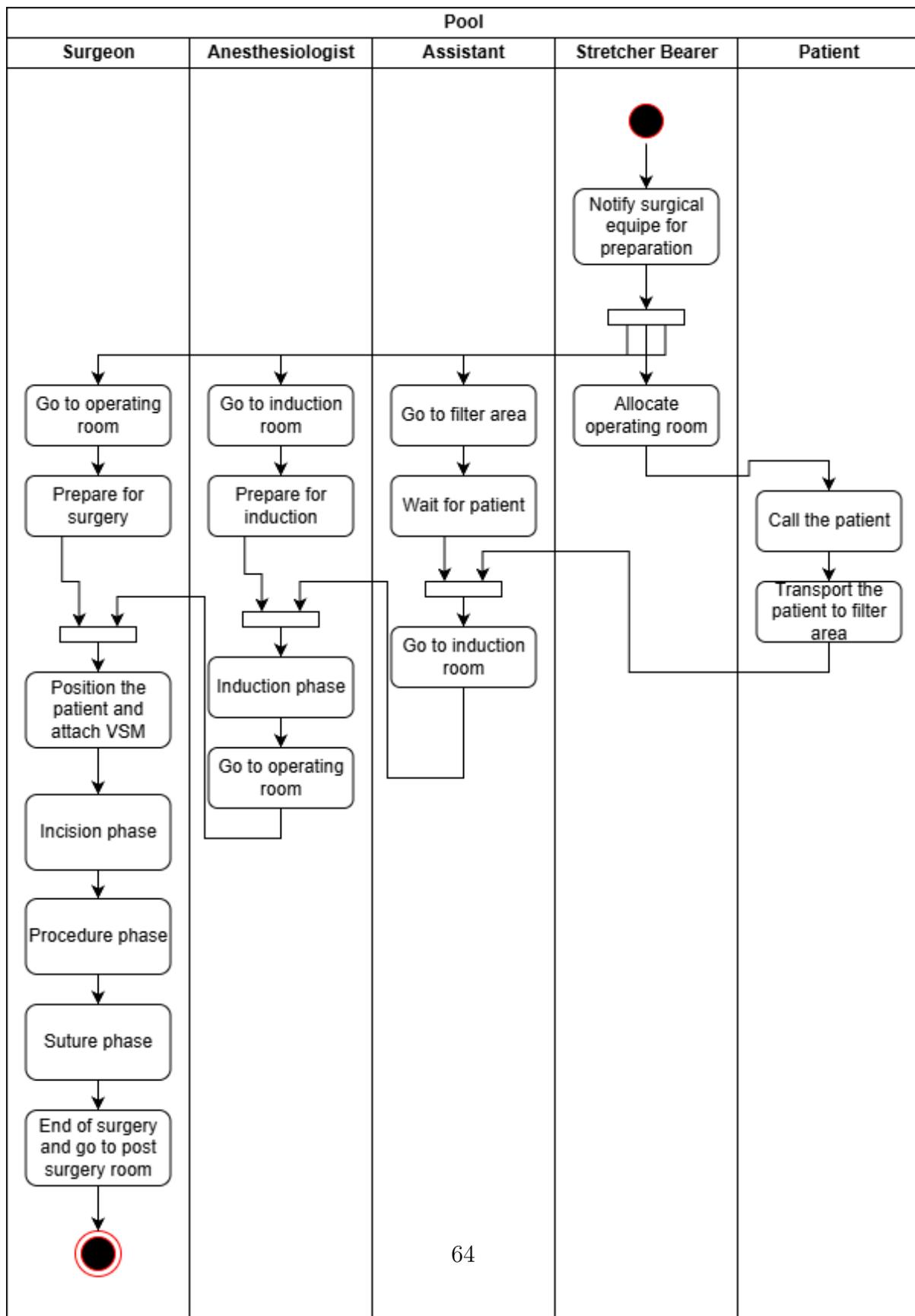
Figure 3.7: Activity diagram of intra-operative phase
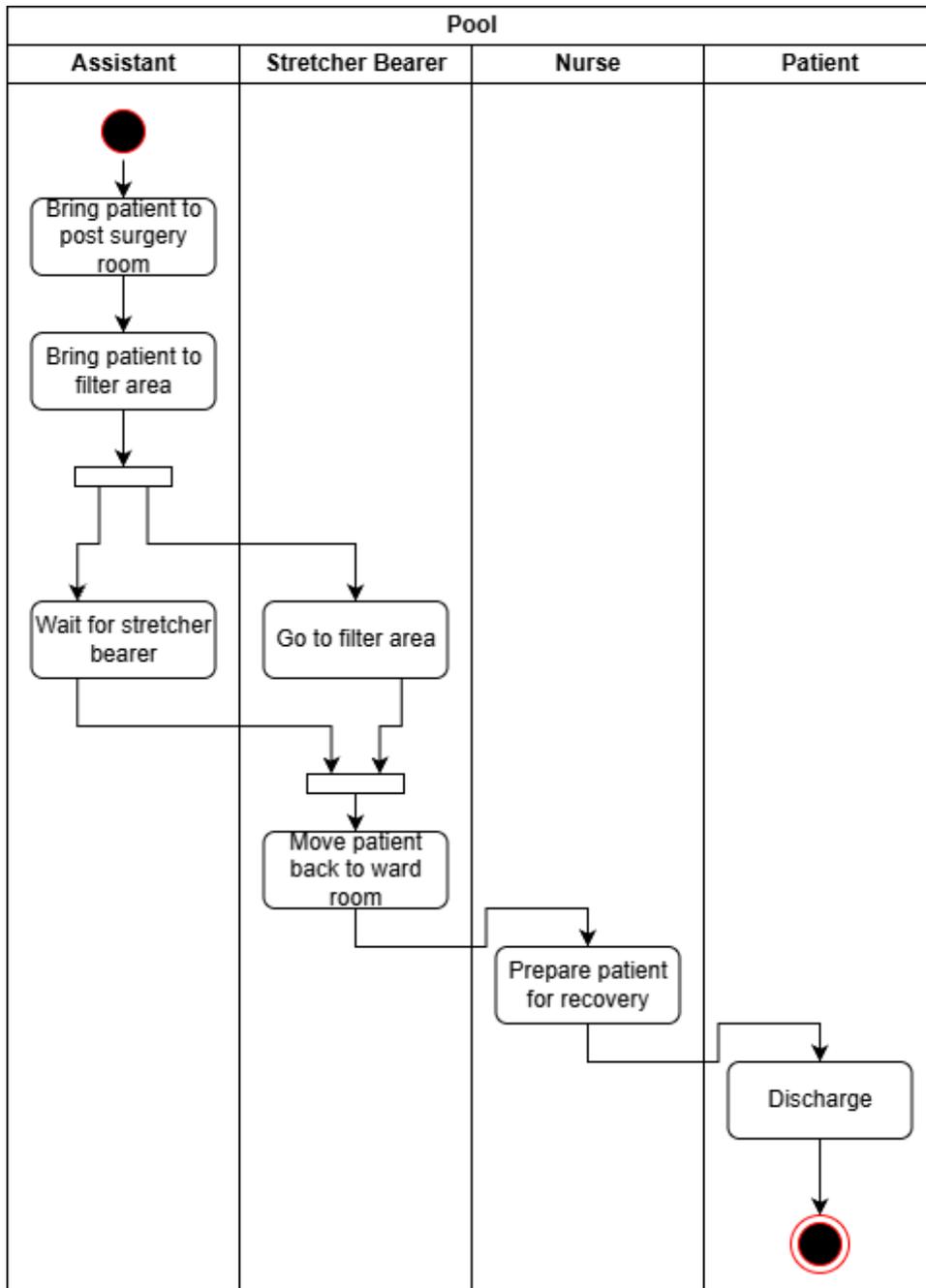
Figure 3.8: Activity diagram of post-operation

Table 3.1: Fundamental events of a surgical path

Order	Event	Acronym	Description
1	Leaving the ward	OutR	When the transport operator takes charge of the patient
2	Patient in filter area	InF	Patient access to the filter and verification of their identity
3	Enter the surgical department	InORB	When the operating room nurse takes charge of the patient
4	Enter the induction room	InSI	Patient enters the induction room
5	Start induction of anesthesia	StAnest	The time when the anesthetic is injected for general anesthesia or injected into the skin for regional anesthesia
6	Patient positioned and ready	PzPr	Patient ready for surgery after completing anesthesia and positioning
7	Enter the operating room	InSO	The patient enters the operating room
8	Start of surgical procedure	StCh	Start of incision
9	End of surgical procedure	EndCh	Last suture point
10	Exit from operating room	OutSO	The patient exits the operating room
11	Enter the recovery room	InRR	Patient entry into the recovery room
12	Exit the recovery room	OutRR	Patient exit from the recovery room
13	Enter the intensive care unit	InUTI	Patient admission to intensive care
14	Exit from the surgical department	OutORB	The patient exits the surgical department
15	Comeback to the ward	InR	When the ward nurse recovers the patient

3.1.8 Ubiquitous language

Table 3.2: Ubiquitous language table

Domain term	Description	Synonymous
Patient	The individual receiving surgical and peri-operative care	hospitalized, care receiver
Surgery	A clinical procedure performed to treat a medical condition through operative techniques	surgical procedure, operation, intervention
Induction	The phase in which anesthesia is administered to prepare the patient for surgery	anesthetic induction
Incision	The surgical cut made to access the operative site	surgical cut, opening
Suture	The act of closing the surgical incision after the procedure	wound closure, stitching
Sanification	The cleaning and disinfection process performed to restore a safe surgical environment	disinfection, room cleaning
Induction room	A dedicated area where anesthesia induction is performed before surgery	anesthesia room
Post-operation room	The area where patients are monitored immediately after surgery	recovery room, PACU
Sterilization room	A facility where surgical instruments are cleaned and sterilized	-
Filter area	A controlled transition zone between clean and contaminated spaces	Change-bed room
Operating room	A sterile room equipped for performing surgical procedures	OR

Table 3.2: Ubiquitous language table (Continued)

Domain term	Description	Synonymous
Emergency OR	An operating room reserved for urgent or unplanned emergency surgeries	urgent OR
Daily slots	Predefined time intervals allocated for surgical activities within a day	time slots, surgical sessions
Waiting list	An ordered list of patients awaiting a surgical procedure	surgical queue
Score	A numerical value representing patient urgency and waiting time	priority score
Priority	The clinical urgency assigned to a patient for scheduling surgery	urgency level
Operating note	A list of surgeries scheduled to be performed the following week or the following day	surgeries schedule
Surgical department	The hospital unit responsible for surgical care and operating rooms	Operating suite, operating block, operating theater, surgical unit
Surgical equipe	The multidisciplinary team involved in performing a surgery	surgical team, medical staff
Nurse	A healthcare professional responsible for patient care	nursing staff
Surgeon	A medical doctor who performs surgical procedures and leads the surgical intervention	surgical doctor

Table 3.2: Ubiquitous language table (Continued)

Domain term	Description	Synonymous
Anesthesiologist	Specialized practitioner responsible for administering anesthesia and monitoring the patient's vital signs during surgery	anesthesia specialist
Stretcher bearer	A healthcare worker responsible for transporting patients between hospital areas using stretchers	patient transporter
Assistant	A healthcare professional who supports the surgeon during the surgical procedure	surgical assistant,
Urgency	A clinical condition requiring timely medical intervention but not posing an immediate threat to life	high priority
Emergency	A critical clinical condition requiring immediate intervention to prevent serious harm or death	critical condition
Pre-operative phase	The period before surgery, including patient preparation and assessment	preparation phase
Intra-operative phase	The period during which the surgical procedure is actively performed	surgical phase, operative phase
Post-operative phase	The period following surgery, focused on recovery, monitoring, and complication prevention	recovery phase
Peri-operative journey	The complete patient experience encompassing pre-operative, intra-operative, and post-operative phases	Peri-operative pathway
Discharge	The formal process of releasing a patient from hospital care after treatment completion	patient release

Table 3.2: Ubiquitous language table (Continued)

Domain term	Description	Synonymous
Acceptance	The administrative and clinical process of admitting a patient into the hospital or surgical pathway	patient intake
Hospital ward	A hospital unit where patients are admitted and cared for before or after surgical procedures	clinical ward
Ward room	A room within a hospital ward where patients stay during hospitalization	patient room
Vital signs monitor	A medical device used to continuously measure and display patient's physiological parameters	physiological monitor
Sign-in phase	The initial safety phase performed before anesthesia to verify patient identity, procedure, and equipment	-
Sign-out	The final safety phase conducted after surgery to confirm procedure completion and documentation	-
Time-out phase	A mandatory pause immediately before incision to confirm patient identity, surgical site, and procedure	-
Hospital	A healthcare facility providing medical, surgical, and diagnostic services to patients	healthcare facility
BLE Sensor	A Bluetooth Low Energy device used to track assets or patients in real time within hospital environments	BLE beacon, proximity sensor

Table 3.2: Ubiquitous language table (Continued)

Domain term	Description	Synonymous
QR Scanning	A process that uses QR codes to record and track events or phases within clinical workflows	barcode scanning

3.2 Context Map

Given the presence of multiple stakeholders, heterogeneous processes, and tightly coupled clinical and organizational workflows, it was necessary to clearly structure the domain knowledge and define precise boundaries among the different areas of responsibility. In this context, thanks to the Domain-Driven Design, the identification of subdomains, the definition of bounded contexts and the construction of a context map play a fundamental role in organizing the domain model, reducing ambiguity and enabling scalable and maintainable system design.

3.2.1 Bounded Context

After an eventstorming session (fig. 3.9) the following Bounded Contexts were found:

- Patient Context: this bounded context focuses on the representation of the patient throughout the peri-operative journey. It includes patient identification, admission status, ward allocation, and the tracking of the patient's location and state before, during, and after surgery. It serves as a central reference for other contexts, while maintaining ownership over patient-related data and lifecycle events.

- Operating Room Context: the Operating Room Context models the physical operating rooms, including room availability, daily time slots (e.g. morning and afternoon sessions), room status (available, occupied, under disinfection), and the association with critical assets such as the VSM.

- Surgery Context: this context encapsulates the surgical procedure itself as a domain concept. It models the lifecycle of a surgery, including its phases (pre-operative,

intra-operative, post-operative), assigned medical staff, timing, and execution status. The Surgery Context keeps track of events related to a specific intervention, interested patient and its information.

- Surgery Department Context: the Surgery Department Context represents the organizational and structural view of the surgical unit. It includes the coordination of multiple operating rooms, schedules and executing surgeries at a departmental level. This context is responsible for high-level analysis across the entire surgical department.

- Vital Sign Monitor Context: this bounded context models the acquisition and management of real-time physiological data generated by medical devices. It includes vital parameters such as heart rate, blood pressure, oxygen saturation, and other monitored signals. The Vital Sign Monitor Context provides time-series data that enrich the Digital Twin of both the patient and the surgical procedure, enabling real-time monitoring and post-operative analysis.

- Supervisioning Context: the Supervisioning Context focuses on monitoring, analytics and decision support. It aggregates information from multiple bounded contexts to provide a global and real-time view of the surgical department. This context is responsible for KPI visualization, anomaly detection, performance analysis, and operational supervision, supporting the medical staff in optimizing workflows and resource utilization.
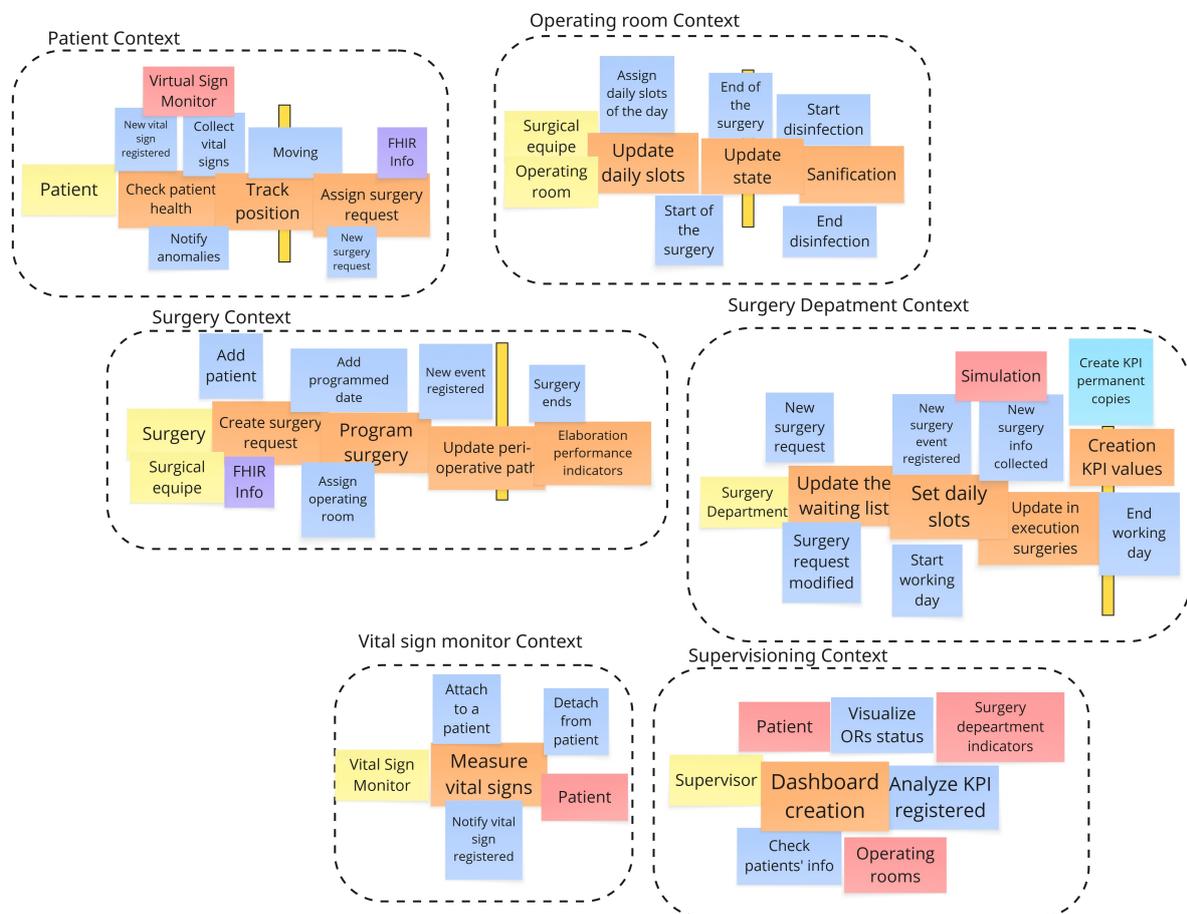
Figure 3.9: Eventstorming outcomes

3.2.2 Subdomains

After identifying the bounded contexts and defining their responsibilities and interactions, the next step in the Domain-Driven Design process is the identification and classification of subdomains. Subdomains represent problem spaces within the overall domain to clarify the strategic importance of each business area, element or activity. In DDD, subdomains are commonly classified into Core, Supporting, and Generic subdomains. This classification is particularly important in complex socio-technical systems such as hospital surgical departments, where not all functionalities contribute equally to strategic value, as we can see in the following table (table 3.3).

Table 3.3: Subdomains descriptions

Name	Classification	Description
PatientManagement	CORE	Subdomain referred to the patient modeling and management
PatientTracking	SUPPORTING	Subdomain referred to patient information tracking and monitoring
SurgeryDepManagement	CORE	Subdomain referred to the department modeling and management
SurgeryManagement	CORE	Subdomain referred to the surgery modeling and management
SurgeryTracking	SUPPORTING	Subdomain referred to surgery events and information tracking and recording
ORManagement	CORE	Subdomain referred to the operating room modeling and management
ORTracking	SUPPORTING	Subdomain referred to operation rooms status and information tracking
VSMManagement	SUPPORTING	Subdomain referred to the VSM modeling and management, with multiple parameters and linkable to any patient
SupervisionManagement	GENERIC	Subdomain referred to the supervisioning system that enables the medical staff and stakeholders to analyze the department performances

3.2.3 Context Map

After defining the contexts, we describe the relationships between them using the Context Map (fig. 3.10).

Table 3.4: Relationships table

Entity 1 (Role)	Entity 2 (Role)	Relationship type
SupervisioningContext (D)	OperatingRoomContext (U)	Open Host Service, Published Language

Table 3.4: Relationships table (Continued)

Entity 1 (Role)	Entity 2 (Role)	Relationship type
SupervisioningContext (D)	SurgeryContext (U)	Open Host Service, Published Language
SupervisioningContext (D)	SurgeryDepartmentContext (U)	Open Host Service, Published Language
SupervisioningContext (D)	PatientContext (U)	Open Host Service, Published Language
SupervisioningContext (D)	VitalSignMonitor (U)	Open Host Service, Published Language
PatientContext (D)	VitalSignMonitor (U)	Anti-Corruption Layer
SurgeryDepartmentContext (SK)	OperatingRoomContext (SK)	Shared Kernel
SurgeryDepartmentContext (SK)	SurgeryContext (SK)	Shared Kernel
SurgeryDepartmentContext (SK)	PatientContext (SK)	Shared Kernel

An Open Host Service and Published Language types relationship was chosen in order to satisfy the *augmentation* property of DTs, as we will see the next step to translate the contexts into Digital Twins. The OHS and PL relationship represents the best way to have a public interface between the upstream and the downstream that is not intended to conform to other ubiquitous languages, exposing functionalities using public APIs and language translations. With OHS + PL the supplier, that is the service that exposes the data, known as the upstream, implements the translation of its internal model: this is exactly what happens by having a digital adapter that prepares the data to be sent to the requests of the application layer (pull logic). The Shared Kernel that uses SurgeryDepartmentContext ensures that there is a shared basis of concepts and functionality: this type of relationship, in particular, facilitate satisfying both the *representativeness* and *composability* properties, even between DTs, as we will analyze later. Finally, the *Anti-*

corruption Layer relationship facilitate the communication between the PatientContext with possible legacy or third-party systems represented by the VitalSignMonitorContext: this should protect the integrity and autonomy of the patient context without being affected by another context that might be an external system instead of a dedicated DT, supporting the *entanglement* and *reflection* properties. When we have a physical relationship (or a composite relationship between two DTs, where one represents a physical asset and the other represents digitalization), we find a push-type logic: data is pushed from upstream to downstream, that is the mirroring between the physical and virtual assets. In this case, an ACL is preferable because data translation and validation occurs within the receiver: this is precisely what happens when using the physical adapter.
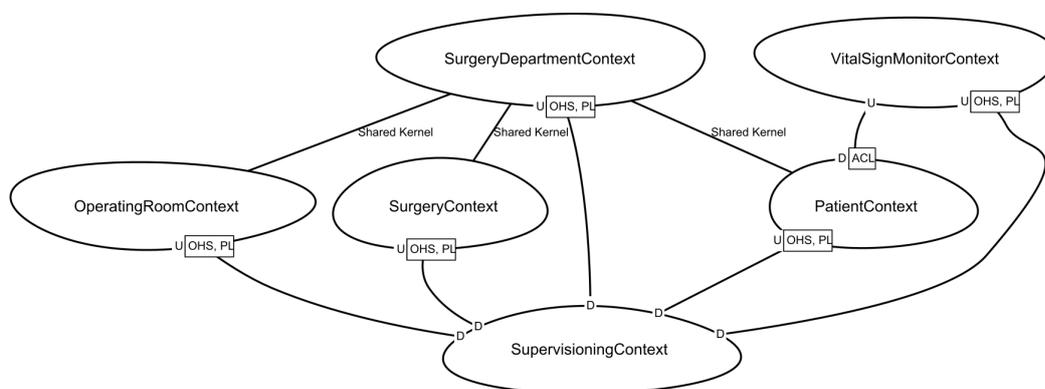
Figure 3.10: Context map with relationships

3.3 From Bounded Context to Digital Twin

Once the bounded contexts have been defined, it is now possible to translate the work done in knowledge crunching phase into the next step, the Digital Twin modeling (fig. 3.11). Following the Context Map, the Digital Twins defined are:

- **SurgeryContext - Surgery DT**: the DT responsible to mirror a specific surgery request, tracking all of its information and fundamental registered events. A surgery is executed on a specific patient, programmed in a specific operating room but can be executed into another, based on the actual room state.

- **PatientContext - Patient DT**: the DT responsible to digitalize the physical patient, with all of the personal information and monitoring vital signs. The patient is subjected to multiple surgeries.

- **OperatingRoomContext - Operating room DT**: this DT will track the physical operating room status and events. The operating room belongs to a single surgery department.

- **VitalSignMonitorContext - VitalSignMonitor DT**: the mirroring of a vital signs monitor that virtualize the physical VSM, keeping track of registered vital signs values of a patient. The VSM belongs to a operating room and is used for a moltitude of surgeries over time.

- **SurgeryDepartmentContext - SurgeryDepartment DT**: this represents the DT of the entire surgical department, that is a composition of all the previously described digital twins, that aggregates data to perform the KPI elaboration and recording. The surgery department supervises all the surgeries which occur into its operating rooms.

3.3.1 Proposed solution

In the proposed solution, the surgical department is supported by a Digital Twin ecosystem designed to continuously mirror all the relevant physical assets involved in surgical operations, including operating rooms, medical devices, patients, and clinical workflows. Each physical entity is associated with its corresponding Digital Twin, enabling the real-time tracking of surgical events, operating room states and patient information throughout the entire peri-operative process. This ecosystem provides a unified and coherent digital representation of the surgical department, allowing data to be collected, correlated, and contextualized across different sources. This ecosystem should be also created according to a Hypermedia Web of Digital Twins approach, enabling the DTs ecosystem to be managed and explored using standard web technologies.

The information gathered by the Digital Twins are leveraged to compute and analyze KPIs which describe the performance, efficiency, safety, and utilization of the surgical department as a whole. These KPIs are made available through a dedicated dashboard,
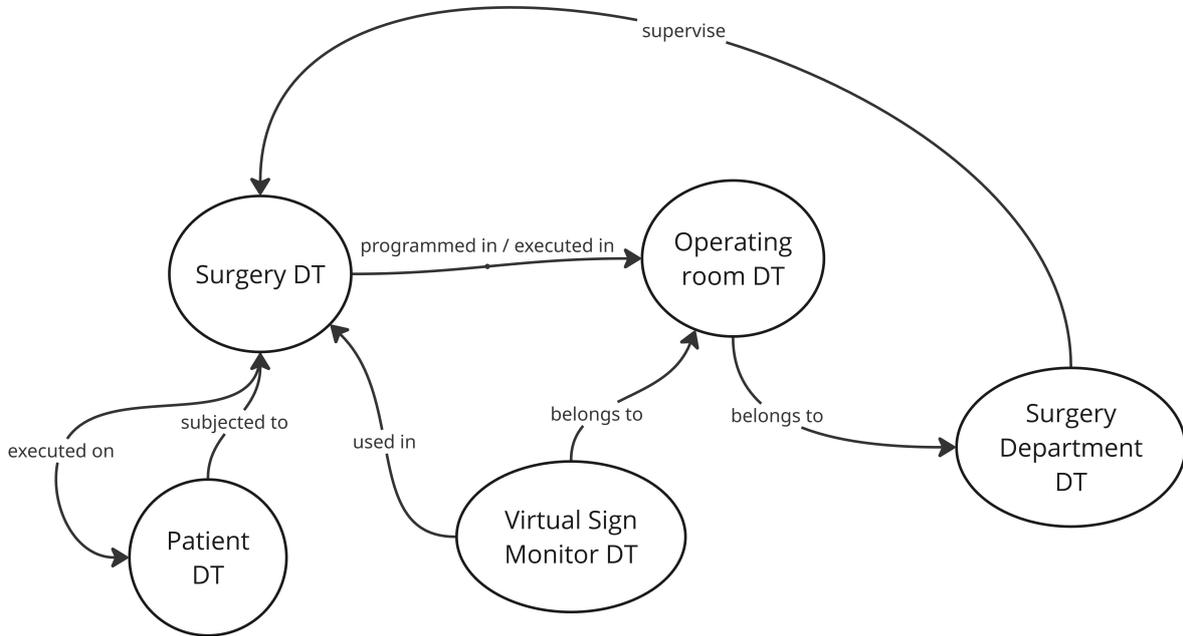
Figure 3.11: Digital Twins ecosystem

which allows medical staff and coordinators to visualize the current state of physical assets through their Digital Twins and monitor ongoing activities. To ensure scalability, reliability, and healthcare compliance, the system is designed around standardized and open technologies and with a strong focus on interoperability, which is a critical requirement in the healthcare domain. The ecosystem supports structured and semantically meaningful data exchange and is compliant with established medical communication protocols.

Finally, an ad hoc simulation is a key point in order to accurately model the surgical department dynamics and validate the DTs utilization, creating a complete architecture from the physical emulation to the top HWoDT level.

3.3.2 Key Performance Indicators

Finally, we can describe the KPIs that support the medical staff to evaluate the peformance, efficiency and effectiveness of the surgical department.

Pre-operatory phase

Table 3.5: KPIs

KPI name	Formula	Description
Waiting list consistency	$\sum pz\,in\,LdA$	Number of interventions not yet scheduled
Waiting time for priority class	$TdA = TRic - TIns$	Waiting times stratified by category
Patients over threshold	$OS = \sum pz\,in\,LdA > CP$	Number of patients above the threshold indicated by the priority class

Intra-operatory phase

Table 3.6: KPIs

KPI name	Formula	Description
Raw utilization	$\frac{\sum OutSOi - InSOi}{tSO}(\%)$	Percentage ratio between the sum of the time patients occupy the operating room and the total assigned hours
Start time tardiness	$STT = StCh - ProgrStart$	Indicates the delay in starting the first surgical procedure of the day
Over time	$OT = OutSO - EndSlot$	The additional time interval during which the OR remains busy
Under utilization	$UU = EndSlot - OutSO$	The time interval during which the OR is not being used at full capacity

Table 3.6: KPIs (Continued)

KPI name	Formula	Description
Turnover time	$TT = InSO_{pz2} - OutSO_{pz1}$	The time interval for OR recovery between one patient and the next
Mean surgical time	$Tchir = EndCh - StCh$	Indicates the average duration of the surgery
Mean anest time	$Tanest = PzPr - StAnest$	The average time interval for the patient to prepare for surgery
Number of surgeries per slot	$N = \frac{nSurgeries}{nSLOT}$	Indicates the density of surgical interventions in a OR
Touch time	$TT = OutSO - StAnest$	Difference between the moment the patient leaves the OR and the start of anesthesia induction
Cancelled surgeries	$CC = \frac{nSurgeries}{nProgrSurgeries}(\%)$	Variability of daily scheduling
Planned utilization rate	$UP = \frac{tProgrammed}{tSO}(\%)$	How accurate and realistic the daily surgical planning is
Long turnover times	$TTP = \frac{nTT>60min}{nTT}$	Ratio between the number of turnover times exceeding 60 min and the total number of turnover times
Emergency SO raw utilization	$\frac{\sum OutSO_u - InSO_u}{tSO_u}(\%)$	Raw utilization for emergency rooms
Emergency cases in elective session	$UinE = \frac{nElectiveUrgencies}{nElective}$	Indicates how much space emergencies have within a regular schedule

Table 3.6: KPIs (Continued)

KPI name	Formula	Description
Value added time	$VAT = \frac{EndCh-StCh}{OutSO-InSO}(\%)$	Expresses the percentage of value-added time out of the total patient transit time

Chapter 4

Design of the architecture

Following the analysis of the domain and the application context presented in the previous chapter, this section focuses on the actual design of the system. The goal is to show how the requirements identified earlier are transformed into a working technical solution. In this chapter, we will describe the overall architecture of the system and explain how its main parts work together. We will look at the fundamental components that make up the system, detailing their specific roles, such as Digital Twins and simulation, and how they interact with each other. This structure provides the necessary foundation for the implementation of the project, ensuring that the system effectively addresses the practical challenges discovered during the initial analysis phase.

4.1 Requirements and quality attributes

Before building the system, it is important to clearly define what it needs to do and how it should behave. These requirements act as a guide for the development process and help ensure that the final project meets the stakeholders and users' needs.

4.1.1 Functional Requirements

- Virtualization of the patient and tracking of his medical and personal information, position in the hospital and perioperative path

- Monitoring patient's vital parameters

- Virtualization of a surgery procedure, modeling specific properties and tracking the fundamental events in time

- Elaboration of specific KPIs about a determined category of surgeries, operating rooms utilization and global department management

- Virtualization of the operating rooms and tracking all of its information, states and events

- Simulate the peri-operative journey of a patient

- Create a high fidelity virtual model and representation of a surgery department, composed by operating rooms and ward

- Simulate the medical staff and their interactions into the surgery department

- Model the OR management and sanification

- Virtualize the patient scanning with indoor virtualized location tracking systems

4.1.2 Non-Functional Requirements and quality attributes

These requirements define the system constraints and quality standards needed to ensure operation in a critical environment such as the surgical department.

- Timeliness: the digital twin must reflect physical changes with short latencies to ensure mirroring consistency

- Scalability: the architecture must allow the addition of new physical assets and digital twins (patients, ORs, BLE sensors and so on) without requiring structural changes to the software

- Availability: the system must be available and guarantee uptime during the department's operating hours

- Correctness: the system must operate in accordance with the established functional specifications and clinical requirements for KPI elaboration and physical assets' tracking

- Reliability: the system should maintain a defined level of performance under given conditions without failures or critical crashes during operative time

- Robustness: the system must behaves correctly against incorrect inputs data of sensors and wrong mirroring (such as physical asset tracing information)

- Interoperability: the system must be capable to interact with standard technologies and other external hospitals systems

- Evolvability: the system should be adapted to new requirements or technologies in a easily manner being hardware agnostic and modular

- Verifiability: digital twins must be verifiable using logging and the simulation to create different scenarios and emulate the physical world

- Usability: ease of use and learning for the surgeons, nurses and medical staff

- Modularity: the system must be modular, in order to adapt the digital twin utilization and capabilities adding and changing components without affecting the base model

4.2 Proposed architecture

The proposed architecture follows a layered approach designed to support the development of a Digital Twin ecosystem for the surgical department, ensuring scalability, interoperability, and semantic data integration (fig. 4.1). The architecture starts from the physical layer emulation, which is reproduced through an ad hoc simulation that models the behavior of the surgical department, surgical processes and assets such as patients and surgeries, and peri-operative events within the operating rooms. This simulated environment represents the physical infrastructure and generates real-time data reflecting the state of the surgical workflow. A bridge layer connects the physical simulation to the Digital Twin layer, enabling the synchronization of physical entities and their digital counterparts. The Digital Twin layer is implemented using the *White Label Digital Twin* framework, which manages the lifecycle of each digital twin. We can think about these three first blocks as the Cyber-Physical Context.
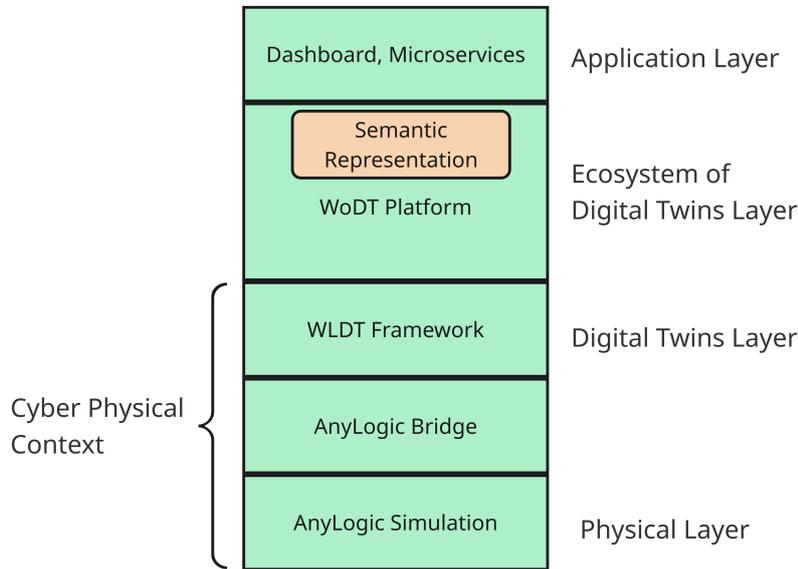
Figure 4.1: Digital Twins stack ecosystem

Above this level, the Web of Digital Twins (WoDT) layer aggregates multiple digital twins into a web-oriented ecosystem platform, providing a high-level semantic representation and enabling standardized interaction between the applications and the DTs visualization and exploration. This layer supports interoperability and facilitates the integration of heterogeneous DTs using standard and interoperable technologies and formats.

Finally, the application layer provides user-oriented services and system functionalities, including a monitoring dashboard and application microservices to access the WoDT platform and elaborated KPIs. These components allow medical staff to monitor DTs and physical assets state and visualize performance indicators.

4.3 Cyber-Physical Context

For the simulation of the physical surgical department, AnyLogic was chosen due to its characteristics to create advanced simulations in an intuitive and integrated way, such as supporting code integration to realize custom behaviors and utilities to allow external communication with other systems.

In our case UDP messages are used to make the simulation communicating with Digi-

tal Twins and enabling the mirroring between the two layers, using MQTT as the tracing message protocol between the bridge and the DTs, as we can see in fig. 4.2. This is made using a bridge middleware, which enables communication between the AnyLogic simulation and the Digital Twin layer, that ensures the synchronization between emulated agents (AnyLogic active components) and their corresponding digital representations. The bridge implements bidirectional communication channels, handling UDP messages generated by the simulation environment and translating them into MQTT messages directed toward the Digital Twin layer, and vice versa.
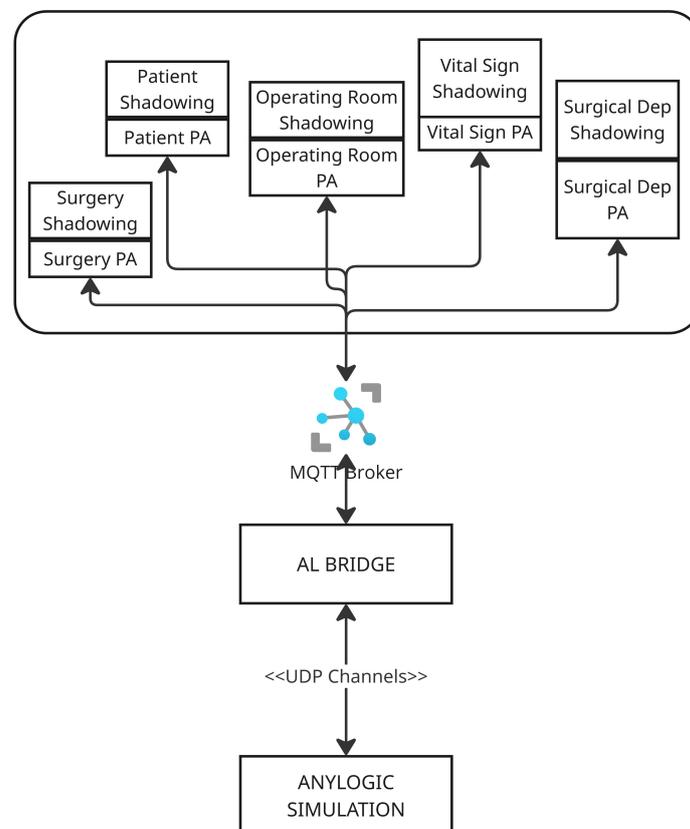

Figure 4.2: Physical emulation and mirroring

Finally, each Digital Twin is equipped with a Physical Adapter, that is responsible to manage the tracking and updating of physical properties, listening for physical events and notifying the shadowing function, as we will see later.

4.4 Digital Twin Layer

This is the core of the entire architecture, the virtualization layer that mirrors the physical surgical department in the various digital twins we have already seen.

4.4.1 Digital Twin template

The Digital Twin layer is designed according to principles derived from Domain-Driven Design (DDD) and the Clean Architecture style, ensuring a clear separation of concerns and high modularity. At its core lies the domain layer, which represents the central component of each Digital Twin and encapsulates the business logic and domain entities of the physical assets, such as patients, surgeries, and operating rooms information. This layer is independent from external technologies and defines the state, rules, and interactions governing the digital representation of the asset. Surrounding the domain layer is
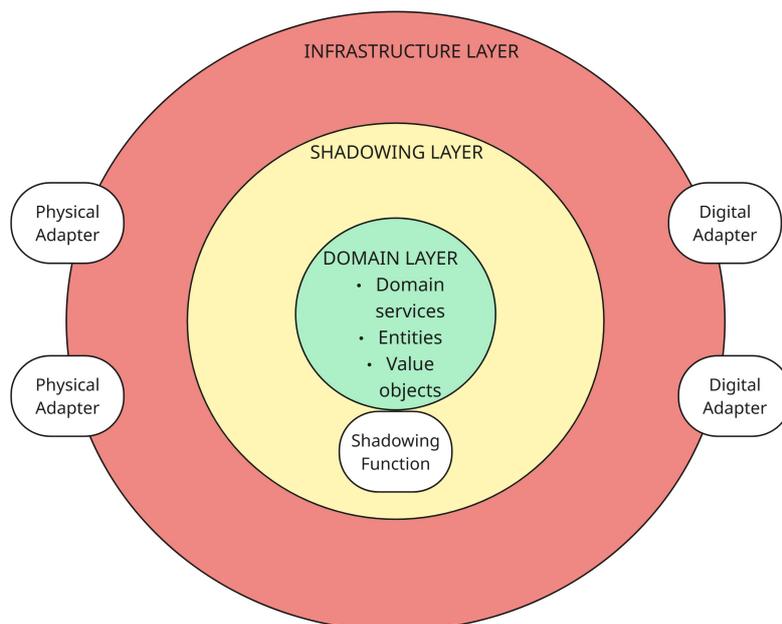

Figure 4.3: Digital Twins clean architecture reference

the shadowing layer, responsible for maintaining the synchronization between the physical entity and its digital counterpart by means of physical adapters. This component

manages state updates, event processing, relationships established and actions management, ensuring that the Digital Twin continuously reflects the real-time conditions of the corresponding physical asset while propagating relevant changes across the system, using digital adapters.

The outermost layer consists of the infrastructure layer, which includes both physical adapters and digital adapters. Physical adapters handle communication with the external physical assets, or simulation assets in our case, while digital adapters enable interaction with higher-level services, applications, and other Digital Twins. This layered architecture promotes scalability, modularity, and technology independence as key quality attributes.

4.4.2 WLDT model

The WLDT framework is designed to maximize modularity, reusability, and flexibility in the development of Digital Twins, enabling the effective mirroring of physical assets into their digital counterparts. The framework provides a general-purpose software entity that can be deployed on cloud or edge environments and attached to physical assets to maintain their digital representations. It simplifies Digital Twin design by offering core functionalities while allowing the extension of features, including support for additional custom communication protocols and data normalization mechanisms (fig. 4.4).
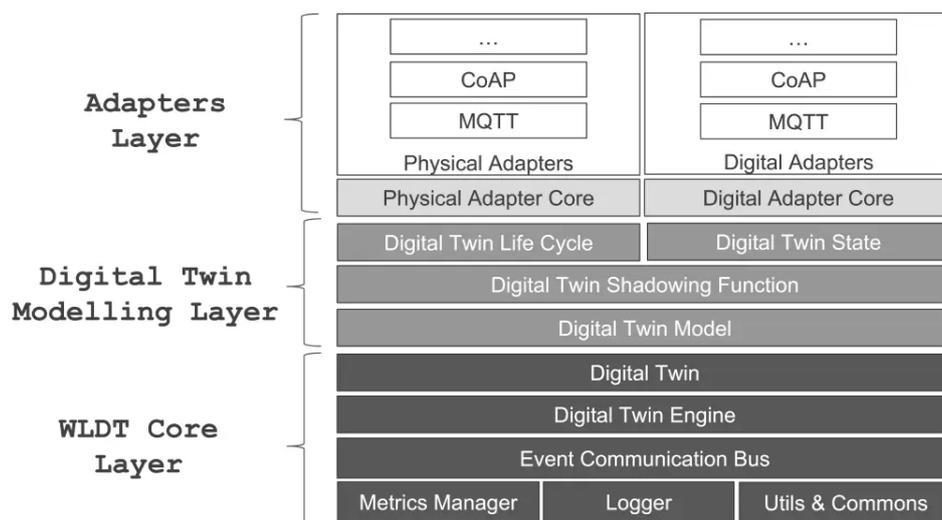

Figure 4.4: WLDT internal structure of a Digital Twin

The design of the framework is guided by three main requirements: simplicity, allowing developers to easily create and customize Digital Twin instances; extensibility, enabling the addition of new functionalities through modular components; and portability with microservice readiness, ensuring that Digital Twins can operate across different platforms as independent software agents. The architecture of the framework manages all the required functionalities of a Digital Twin, from physical tracking to shadowing process and finally the digital communication protocols. It is structured into three main levels: the core library, the Digital Twin modeling layer, and the adapter layer responsible for interaction with external systems (fig. 4.4). The shadowing process is based on the Digital Twin Model, that provides an abstract representation of the physical asset, defined in terms of:

- Properties: describe observable attributes of the physical asset as labeled data that dynamically evolve over time

- Events: represent domain-level occurrences associated with the physical asset

- Relationships: model the connections between the asset and other physical entities through links to their corresponding Digital Twins, reflecting the operational context rather than the asset's intrinsic state

- Actions: define the operations that can be executed on the physical asset through the Digital Twin or directly within the digital environment, potentially extending the physical capabilities

As a consequence of this, it is possible to model our DTs with properties, events and relationships, with the main ones shown in the following tables.

Table 4.1: Patient model

Property	Description
Patient nominative	Name and surname of the patient
Gender	The gender of the patient
Birth date	The birth date of the patient

Table 4.1: Patient model (Continued)

Property	Description
Identifier	Identification code that uniquely identifies the patient
Current location	Current location name of the patient
Heart rate	Current heart rate value
Event	**Description**
Surgery request	A new surgery is requested for the patient
Bpm anomaly	A bpm anomaly situation is detected inside the DT
New heart rate	The heart rate property has been updated and the new value is propagated
Relationship	**Description**
Located in	The place where the patient is located, the relationship does not exist if the patient has been discharged
Surgery	Relationships with interventions (even past ones) in which the patient has been involved

Table 4.2: Surgery model

Property	Description
Reason and priority	Human readable eason and priority code of the surgery
Category and code	Textual name and identification code of the surgery's category

Table 4.2: Surgery model (Continued)

Property	Description
Insertion date	The date the surgery was added to the waiting list
Admission time	Date and time of the patient's hospital admission
Identifier	Identification code that uniquely identifies the surgery
Programmed date	Date on which the intervention is scheduled to be performed
Execution start/end time	Timestamp of the start/end of the surgical procedure
Fundamental events timestamps	List of timestamps related to each peri-operative step
Estimated time	Estimated time to complete the surgical procedure
Event	**Description**
Surgery started/terminated	Surgery started/terminated event
New event registered	A new peri-operative event is registered for the surgery
Warning	A generic warning with specific information is generated
Is cancelled	The surgery has been cancelled
New measured KPI	New KPI value related to the surgery has been elaborated
Relationship	**Description**
Patient	The patient to be operated

Table 4.2: Surgery model (Continued)

Property	Description
Programmed in	Programmed operating room to be used for the procedure
Executed in	Actual operating room used for the procedure

Table 4.3: Operating room model

Property	Description
Status	Current status of the operating room
Last disinfection	Timestamp of the last disinfection made
Name	Name of the operating room
Id Room	Identification number of the OR
Event	**Description**
Assign daily slots	Event meaning that slots have been assigned for the day
Added new slot	New slot is added or modified
Disinfection started/terminated	Event occurred when disinfection process is started/finished
Now available	The OR is now available and ready
Busy	The OR is busy and not ready to be used
Relationship	**Description**
Belongs to	The related surgical department which the OR is part of

Table 4.4: Vital Signs Monitor model

Property	Description
Serial code	Identification code that identifies the device
Current patient ID	Currently attached patient identification code
Device status	Actual status of the device
Current heart rate value	Last heart value registered. Same for other vital signs
Event	**Description**
Attach patient	A patient is attached to the monitoring device
New measurement	A new measurement is registered
Relationship	**Description**
Belongs to	Operating room in which it is located
Patient monitored	The patient attached to the device

Table 4.5: Surgical department model

Property	Description
Current working day	Current working date
Department name	Name of the department
Event	**Description**
Working day started/terminated	Events occurred when the working day is started/finished
New surgery KPI value	Recorded a new KPI for the intervention in progress

Table 4.5: Surgical department model (Continued)

Property	Description
New surgery event	New surgery event is registered
Relationship	**Description**
Supervise	Surgery supervised and managed into the surgical department
Operating room	Operating rooms that are part of the department

4.4.3 Composition of Digital Twins

In the proposed architecture, Digital Twins are composed according to a hierarchical mirroring approach, where the traditional physical–digital mirroring paradigm is extended to interactions among the Digital Twins. Specifically, a Digital Twin can act as a physical asset, exposing its state and behavior to other Digital Twins as if it were their physical counterpart. This enables a form of Digital Twin composition in which higher-level Digital Twins mirror the state of lower-level ones, creating a multi-layer representation of the system by means of physical adapters and digital adapters interaction. Through this mechanism, the mirroring process is not limited to physical assets but is generalized to digital entities, allowing aggregated or composite Digital Twins to be constructed from the state and behavior of other Digital Twins. This approach enables complex system representations while preserving the consistency and synchronization principles of the Digital Twin paradigm. As is shown in the fig. 4.5, the first composition used is related to the interaction between the Virtual Signs Monitor DT and the Patient DT: the VSM track the patient's vital information mirroring the physical device, and the Patient DT does not directly interact with the physical monitoring equipment, instead, it observes the state exposed by the Vital Signs Monitor Digital Twin, treating it as its physical data source. This layered mirroring approach enables decoupling between sensing devices and patient representation. Same thing happens with the surgery department DT, which aggregates and mirrors the state of both Surgeries and Operating Rooms Digital Twins to provide a comprehensive representation of the surgical environment and collecting all the necessary information to elaborate KPIs about the operating rooms performance.
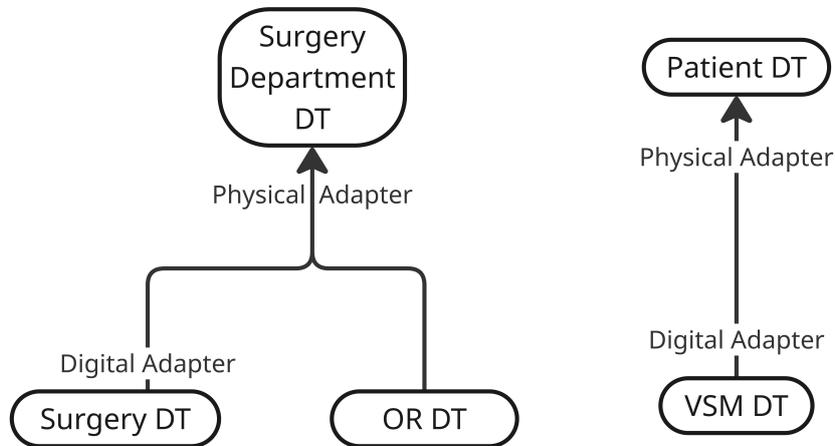
Figure 4.5: Digital Twins composition

4.5 HWoDT Layer and interoperability

The Web of Digital Twins (WoDT) concept describes an open, distributed ecosystem of interconnected Digital Twins that mirror dynamic and interrelated real-world assets, overcoming traditional siloed and domain-specific approaches. In this vision, each Digital Twin operates as an independent service (DT-as-a-service), exposing its capabilities and maintaining a model composed of properties, relationships, actions, and events. These Digital Twins are linked according to the relationships between their corresponding physical assets, forming a dynamic and interoperable digital ecosystem (fig. 4.6).

Due to the increasing technological heterogeneity of Digital Twin platforms and implementations, the Hypermedia-based WoDT (HWoDT) extends the WoDT vision by adopting Web standards, REST principles, and a uniform semantic interface to hide technological differences and enable seamless interaction with heterogeneous Digital Twins. This approach allows applications to access Digital Twins through a consistent service interface, regardless of their underlying technologies, making it particularly suitable for open and collaborative environments involving multiple stakeholders, enabling discovery, interaction, and composition of Digital Twins that may be shared across different platforms [12].
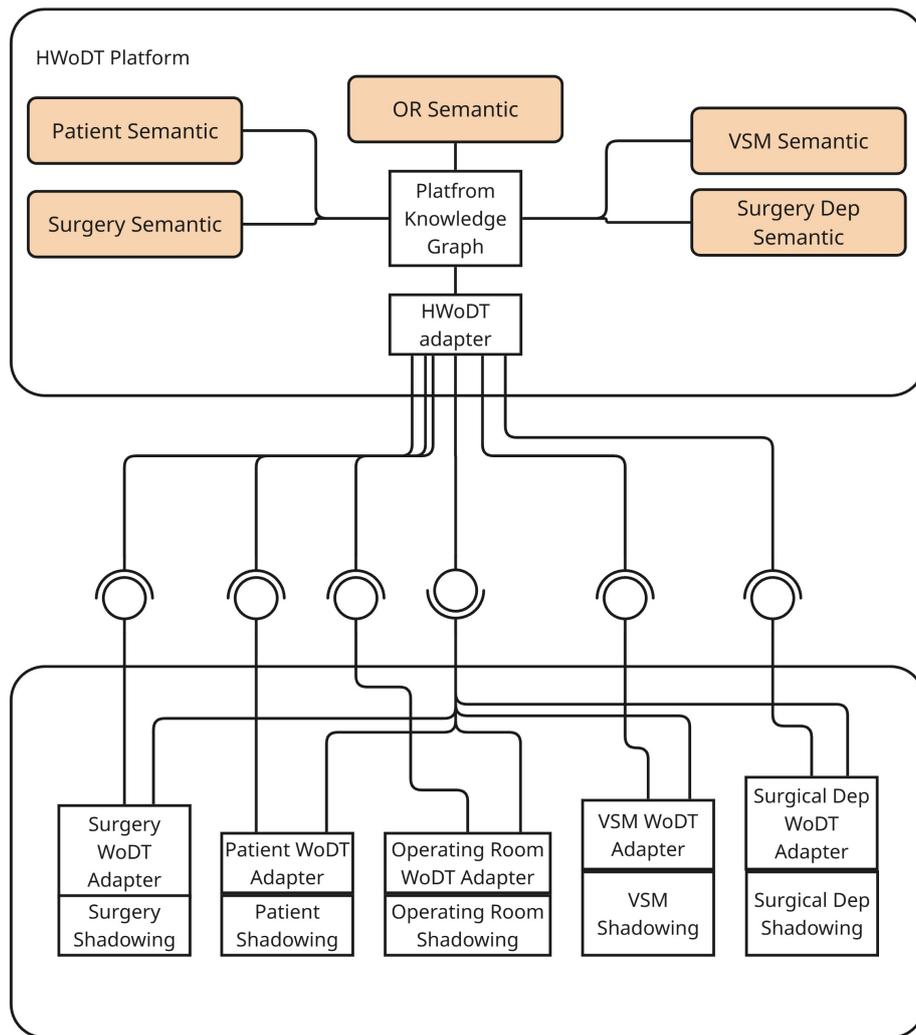
Figure 4.6: HWoDT global scheme

4.5.1 Semantic representation of DTs

As mentioned in previous chapters, integration is a fundamental characteristic that ensure a structured and technology agnostic exchange of healthcare data. There are several standard framework proposals on the market that support the creation of a level of interoperability between different systems, such as openEHR, FHIR and SNOMED CT. We will focus on the last two frameworks and their integration, and more specifically a direct semantic representation of Digital Twins using FHIR resources (fig. 4.7):

- Operating Room DT - Location resource

- Surgical Department - Location resource

- Patient DT - Patient resource

- VSM DT - Device resource
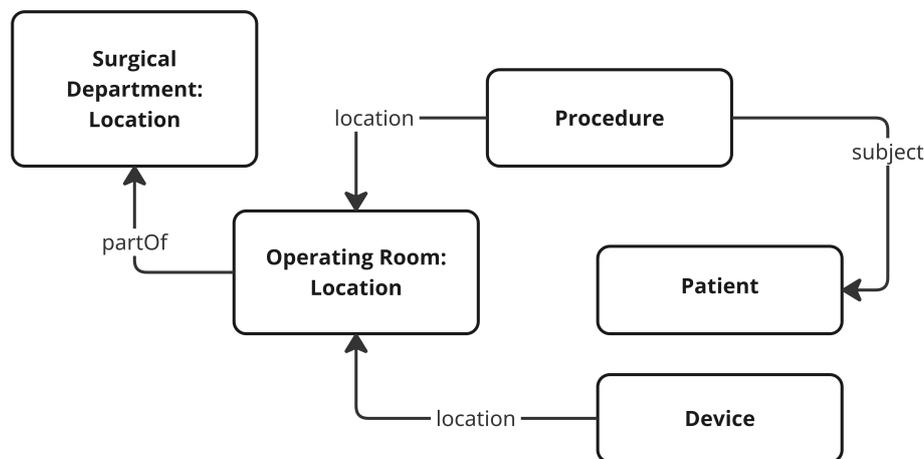
- Surgery DT - Procedure resource

Figure 4.7: FHIR Resources

4.6 Deployment

The deployment of the final system, as seen in the previous sections, is structured to ensure a clear separation between the physical simulation layer, the Digital Twin ecosystem

and the application layer. The agent that simulates the physical asset of each Digital Twin communicates with its virtual counterpart through the bridge middleware, which enables bidirectional message exchange and guarantees real-time synchronization with the physical adapter that intercepts events and properties. Then, we have the shadowing component, which implements the core logic and manages the effective mirroring process between the physical asset and its digital representation (fig. 4.8). On the ex-
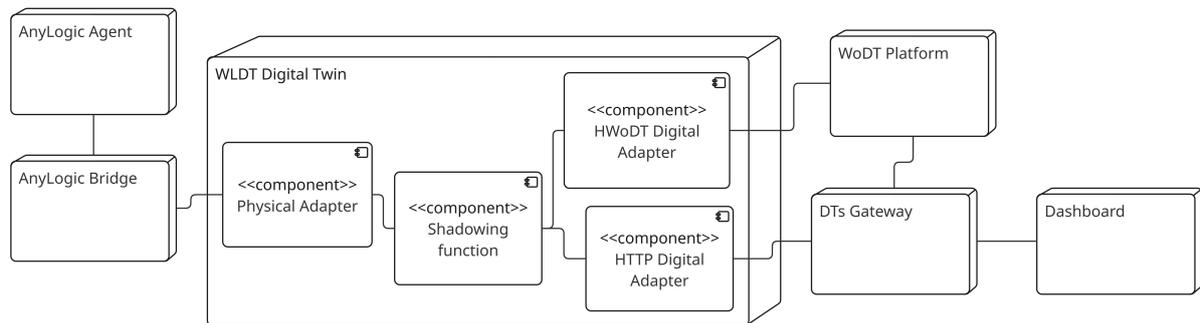
Figure 4.8: Deploy UML scheme

ternal side, two digital adapters are provided: one connects the Digital Twin to the HWoDT platform, exposing it through a uniform web-based interface, while the other enables communication with the application layer, supporting dashboards and microservices. We can see the final deploy scheme in fig. 4.9, that shows all DTs structure and the adapters used to create the composition pattern.
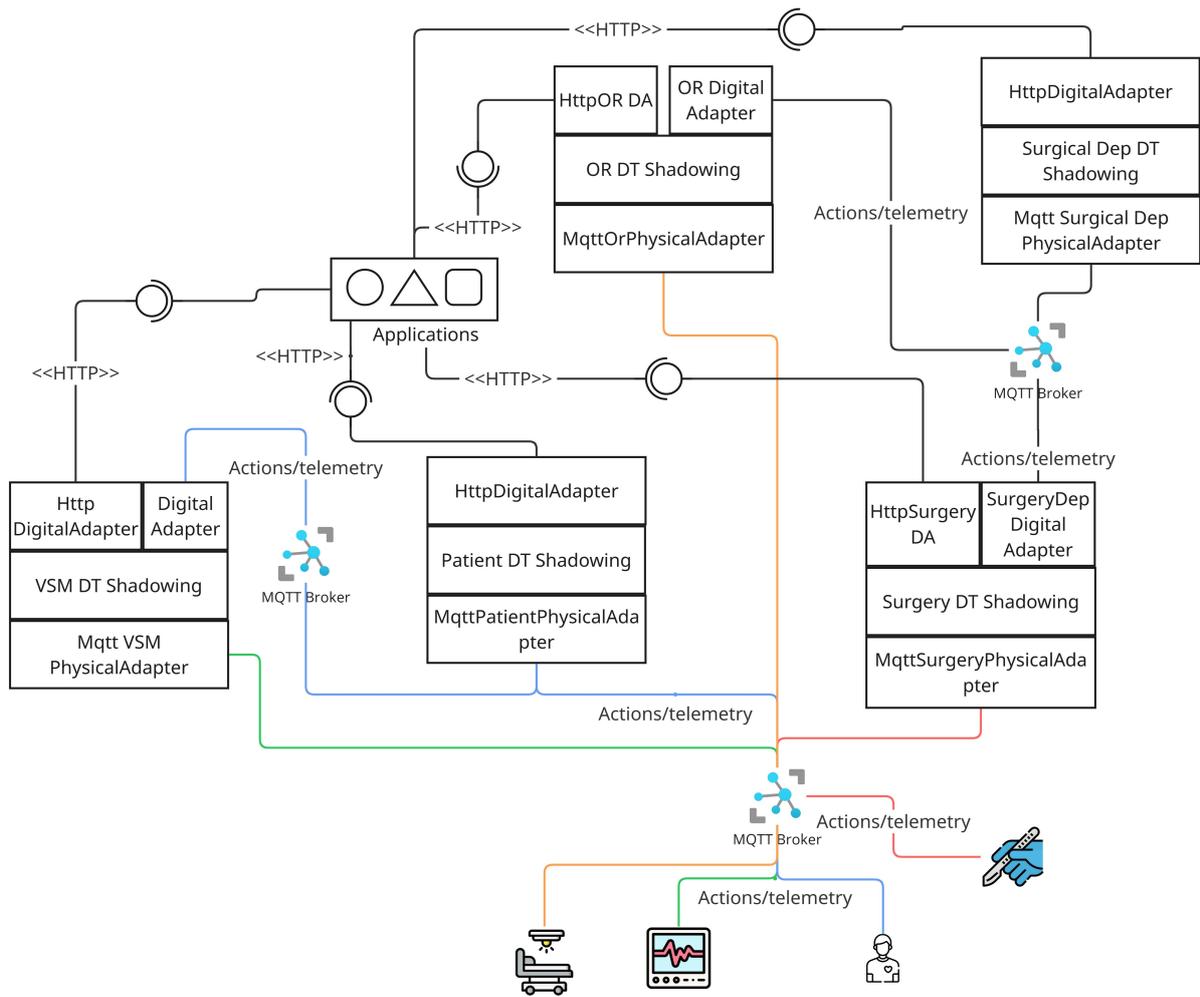
Figure 4.9: Final deploy of Digital Twins

Chapter 5

Implementation

This chapter will focus on the relevant technical aspects and implementation details, describing the practical implementation of the already proposed architecture, in particular starting from the simulation of the physical surgical department up to the upper HWoDT level.

5.1 Simulation of the physical layer

The simulation modeling starts with the virtualization of the peri-operative flow and every related assets that will interact with each other. AnyLogic was selected as the simulation platform to emulate the physical layer of the proposed system and reproduce the patient journey inside the surgical department, supporting an agent-based and discrete-event modeling within any type of complex environment. The Process Modeling Library provided by AnyLogic was adopted to model the peri-operative process of a surgery, as it offers a set of high-level components specifically designed to represent workflow-driven and resource-oriented simulations. The library enables the representation of structured processes such as patient admission, induction, surgery execution, and post-operative activities through a flowchart-based approach and intuitive blocks, making it particularly suitable for capturing the sequence of activities and constraints analyzed during the design phase.

5.1.1 Agents and pools

The first thing to model are the agents that will interact in the workflow:

- Patient: the emulation of the physical patient

- Surgery staff: surgeon, anesthesiologist and assistant

- Healthcare personnel: nurse and stretcher bearer

- Devices: vital signs monitor for patient vital signs tracking emulation and BLE router for position tracking emulation

- Bridge agent: the middleware agent that connects the simulation with digital twins through the AL Bridge software component, receiving events to be sent and translating them into UDP format

In particular, the Bridge Connection agent is the one responsible for receiving all the messages from the agents to be sent to their related virtual representations, such as the Patient agent sending events or property changes to its digital twin (fig. 5.1).
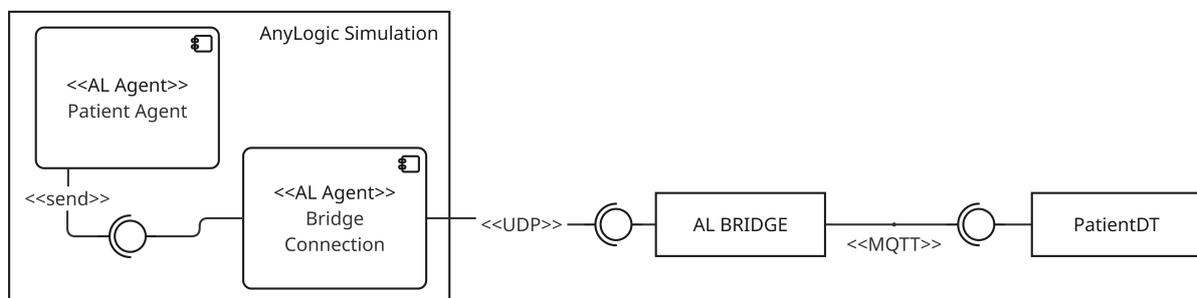
Figure 5.1: Example of agent information tracking

Specific types of agents are then grouped into pools to model a variable number of available resources, in order to analyze the simulation behavior under certain conditions. Pools are used to model the number of healthcare personnel available in the surgical department, such as nurses, surgeons, anesthesiologists, and assistants. An internal tracking system is simulated to implement indoor patient location tracking within the surgical ward by emulating BLE routers, for nearby patients who are assumed to be wearing some sort of Bluetooth bracelet.

5.1.2 Agents coordination

The coordination between agents is a fundamental aspect of the surgical process simulation, as each phase of a surgery requires the availability and synchronization of multiple resources. In order to execute a surgical procedure, all required actors and resources must be properly allocated and ready before the process can proceed. For instance, the stretcher bearer must wait for the patient to arrive in the filter area accompanied by the nurse, while the start of the surgery requires the anesthesiologist to complete the anesthesia and the surgeon and assistant to be present and ready in the operating room. Each agent should also move independently of others, not sequentially, as in a pipeline: as soon as the agent is assigned, it should move to the desired location, preparing to execute the task and waiting for the resources to arrive, in order to simulate the ordinary workflow. These coordination mechanisms are modeled and implemented in AnyLogic using agent statecharts (fig. 5.2) to represent the lifecycle and behavior of each agent, message exchanges to notify state changes and trigger actions and movements, while Process Modeling Library blocks, such as *Seize* and *Hold*, are used to enforce synchronization constraints by waiting until all required resources are available and properly allocated (fig. 5.3). This approach enables the simulation to reproduce realistic dependencies and interactions among the actors involved in the peri-operative workflow.

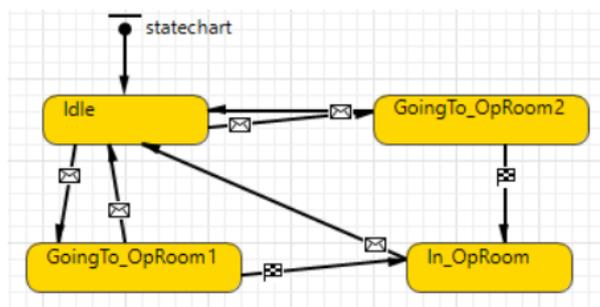Figure 5.2: Statechart of the surgeon

5.1.3 Peri-operative workflow

Simulation's starting layout is based on an existing project ([31]) and is inspired by the classic layout of a surgical department at AUSL Emilia Romagna, such as the Cervesi Hospital planimetry [25] (fig. 5.4). The perioperative simulation is based on the activity
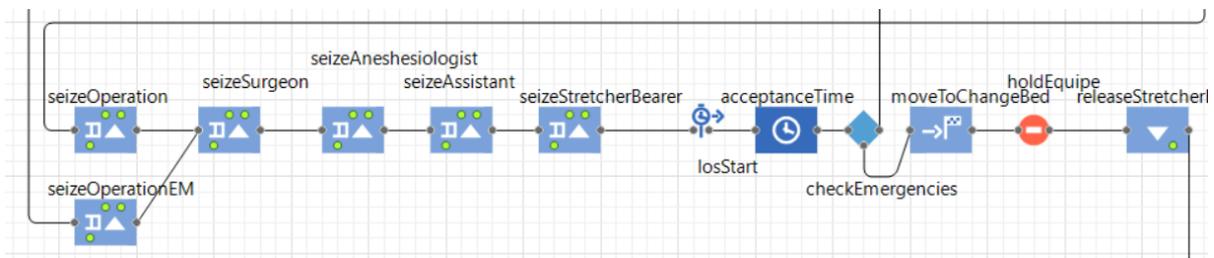
Figure 5.3: Seize and Hold blocks for surgery resources allocation
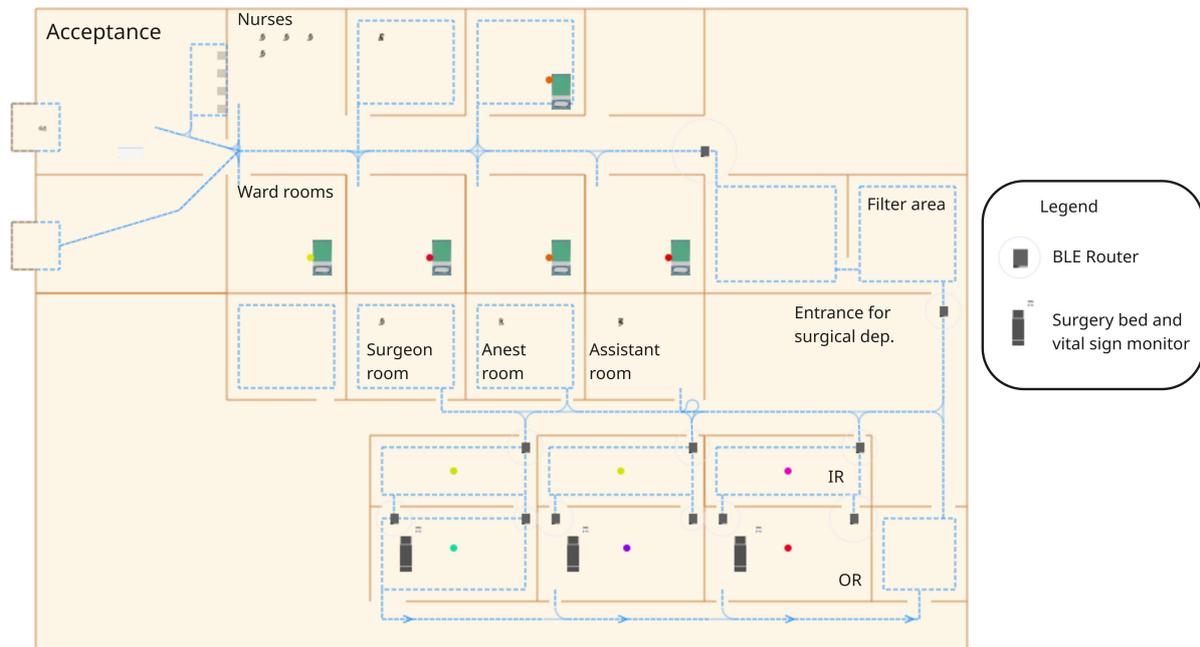
Figure 5.4: Layout of the simulated surgical department

diagrams of the entire surgical pathway of a patient analyzed in the previous chapters
and begins with the patient's admission through the acceptance: here the patient is
welcomed by the nurse and admitted to the ward, which consists of several bedrooms
and is separated from the surgical area by the filter area: the compartmentalization
of the ward is clearly visible. Each operating room has its own induction room, with
dedicated access. BLE routers are distributed throughout the department to precisely
monitor patient positioning and surgical events.

Operating room disinfection

The simulation of operating room sanification is implemented in AnyLogic using the *Downtime* block, which models the cleaning and disinfection procedure that takes place immediately after the completion of a surgery. This mechanism temporarily makes the operating room unavailable, accurately representing the real-world constraint that prevents new surgical procedures from being scheduled until the environment has been properly sanitized. The downtime process is automatically triggered at the end of a surgery and lasts for a predefined duration corresponding to the sanification task. Additionally, the downtime block is designed to notify the corresponding Operating Room DT when the sanification process starts and when it is completed, enabling the synchronization between the physical simulation layer and the digital representation.

Vital Sign Monitor

The Vital Sign Monitor agent represents the device responsible for continuously monitoring the physiological parameters of patients during surgical procedures. In the simulation environment developed with AnyLogic, each operating room is equipped with a dedicated VSM agent that establishes a connection with the patient agent when the patient enters the operating room. Once connected, the VSM starts generating values for the modeled vital parameters, such as heart rate. These measurements are then transmitted to the corresponding VSM DT, which processes the data and propagates the updates to the Patient DT through composition.

Surgery priority and emergencies simulation

Emergency surgeries are also modeled within the simulation to represent unplanned procedures that must be performed within strict time constraints. These surgeries typically originate from critical situations, such as patients arriving from the emergency department, and therefore have maximum priority over the daily scheduled surgical activities. When an emergency occurs, the system dynamically allocates the required resources, potentially interrupting or rescheduling planned operations to ensure timely treatment, as we can see the *checkEmergencies* block in fig. 5.5. Unlike scheduled surgeries, emergency procedures are not currently associated with a dedicated Digital Twin, as they represent unpredictable events that arise suddenly and are not planned in advance. However, this

aspect represents a potential future development of the system, where Digital Twins could be instantiated just-in-time to mirror emergency surgical processes and enable real-time monitoring and management of these critical events.

Intra-operative phase

The intra-operative phase of the surgical process is simulated by modeling each main surgical step, that are induction, incision, and suture, using dedicated delay blocks. These blocks represent the duration of each activity and allow the simulation to reproduce the temporal evolution of the procedure within the operating room, with stochastic parameters in order to introduce possible random delays or advances in execution time.
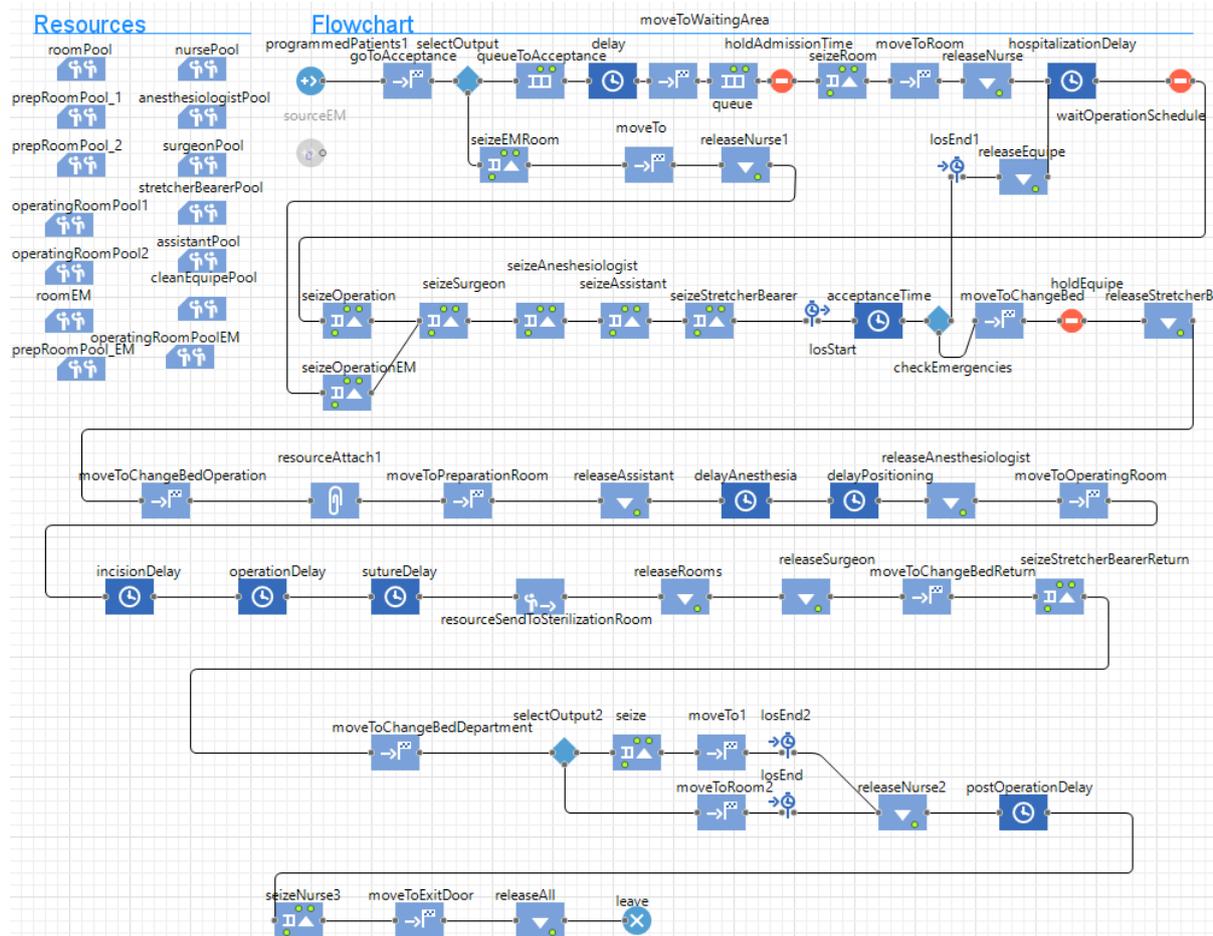

Figure 5.5: Global flowchart of the peri-operative process

5.1.4 Digital Twin communication

The communication between AnyLogic simulation and DTs is performed through the *Bridge Connection* agent, a specific AnyLogic agent that receives all the data generated by other agents and redirects them to their DTs, using the AL Bridge as middleware. The following code shows different portions of patient agent code that aims to update its DT state by sending new surgery events to the bridge: the bridge will then send the events to the AL Bridge using UDP connection (listing 5.1).

```
// update surgery property specifying the property as topic
connections.send(Map.of("id", surgery_id,
        "type","surgery",
        topic, value),
 bridge);
// send new surgery event registered
String timestamp = getTimestamp();
String content = String.format("""
        {
            "event": "%s",
            "timestamp": "%s"
        }
        """, event, timestamp);
connections.send(Map.of("id", surgery_id,
        "type","surgery",
         "updateSurgeryState", content),
 bridge);
```

Listing 5.1: Example of surgery update messages

Finally, the AL Bridge translates the UDP message in a format suitable for MQTT transmission, using a specific structured topic: `anylogic/id/$entityType/$entityID`. BLE router emulation, associated with a specific area name, scans nearby patients and sends updates to their digital twins with their new peri-operative event and location. The BLE router can detect whether the patient is already connected or not, to avoid multiple scans (listing 5.2).

```
List<Patient> patientsList = getDefaultPopulation().stream().filter(g -> g
    instanceof Patient).map(g -> (Patient) g).toList();
for ( Patient patient : patientsList ) {
 double dx = x - patient.getX();
 double dy = y - patient.getY();
 double dist = sqrt( dx*dx + dy*dy );
 if( dist <= radius ) {
  patient.distance = (int)dist;
  patient.router = this.getId();
  if(patient.bleConnected == "FALSE") {
   patient.secCounter = 0;
   patient.bleConnected = "TRUE";
   patient.updateSurgeryEvents(areaName);
  }
 }
}
```

Listing 5.2: Patient scanning

5.2 Digital Twin Layer

The Digital Twin layer represents the core layer of the proposed architecture, as it is responsible for creating, managing, and maintaining the virtual counterparts of all physical assets involved in the surgical environment. *WLDT* is the framework used to implement all digital twins in a modular way, supporting the shadowing process through specific physical adapters and application-level access to the digital twin states through digital adapters

5.2.1 Physical Adapters

The physical adapters represent the entry point of the shadowing process within each Digital Twin, enabling the acquisition of data from the physical or simulated environment and its integration into the virtual representation. Their primary role is to receive,

interpret, and translate incoming information from physical assets into domain-compliant data structures that can be processed by the Digital Twin.

The implementation of physical adapters is based on MQTT technology, which is particularly suitable for continuous monitoring scenarios due to its publish–subscribe communication model and message-oriented interaction. This approach enables efficient transmission of real-time updates related to asset states, supporting the continuous tracking of properties and events generated by the simulated or real physical layer. Each Digital Twin use a specific base topic, that follows the structure seen in the previous AnyLogic section, as we can see in the Surgery DT example code (listing 5.3).

```java
public MqttSurgeryPhysicalAdapter(String idDT, String host, Integer port,
    SurgeryProperties properties) throws
    MqttPhysicalAdapterConfigurationException {
        this.builder = MqttPhysicalAdapterConfiguration.builder(host, port);
        this.baseTopic = "anylogic/id/surgery/" + idDT + "/";

        builder.addPhysicalAssetEventAndTopic(SURGERY_EVENT_KEY, "text/plain",
            this.baseTopic + SURGERY_EVENT_KEY, content -> {
            SurgeryEvents event = SurgeryEvents.valueOf(getJsonField(content,
                "event"));
            String timestamp = getJsonField(content, "timestamp");
            return new SurgeryEventInTime(idDT, event, timestamp);
        });
        ...
    }
}
```

Listing 5.3: Example of physical events listening for SurgeryDT

Each physical adapter defines the observable properties, domain events, and available actions associated with the Digital Twin. These elements are coupled with specific callback mechanisms responsible for translating incoming data from external sources into the internal domain model of the Digital Twin, ensuring compliance with the Clean Architecture principles adopted in the system. Once the data is received and properly transformed, it is captured by the shadowing process, which updates the Digital

Twin state and maintains synchronization between the physical asset and its virtual counterpart. The physical adapter is also responsible for generating the Physical Asset Description, which is required for DT state mapping and the shadowing process.

5.2.2 Shadowing process

The digital twin lifecycle spans over several phases, and the most important one is the shadowing process after events and state synchronization. The shadowing function is responsible to build and maintain updated the state of the digital twin, mapping and updating all properties, events, actions and relationships. The starting point of the shadowing process is the *onDigitalTwinBound* method, that has the responsibility of initialize the DT state and relationships mapping, as we can see the PatientDT example (listing 5.4): it first creates an empty PAD to add the relationship types, then adds it to the PAD map generated from the physical adapters associated with the digital twin, with all physical properties, events and actions already defined into each physical adapter.

```
@Override
protected void onDigitalTwinBound(Map<String, PhysicalAssetDescription>
    adaptersPhysicalAssetDescriptionMap) {
    PhysicalAssetDescription pad = new PhysicalAssetDescription();
    this.subjectedToRelationship = new
        PhysicalAssetRelationship<>(SURGERY_RELATIONSHIP_NAME,
        SURGERY_RELATIONSHIP_TYPE);
    this.currentlyLocatedRelationship = new
        PhysicalAssetRelationship<>(LOCATED_IN_RELATIONSHIP_NAME,
        LOCATED_IN_RELATIONSHIP_TYPE);
    pad.getRelationships().add(subjectedToRelationship);
    pad.getRelationships().add(currentlyLocatedRelationship);
    adaptersPhysicalAssetDescriptionMap.put("relationship_pad", pad);
    super.onDigitalTwinBound(adaptersPhysicalAssetDescriptionMap);
}
```

Listing 5.4: Example of physical events listening for SurgeryDT

Another important part of the shadowing process is the continuous update of properties, that are intercepted by the shadowing process through the *onPhysicalAssetPropertyVariation* method, as we can see in the following PatientDT heart rate property example. We can see the heart rate property update, with related check based on previous registrations to detect anomalies, with a simple example of heart rate check evaluating a mean of last N values: this will generate an notification event for digital applications to alert the abnormal situation.(listing 5.5).

```java
@Override
protected void
    onPhysicalAssetPropertyVariation(PhysicalAssetPropertyWldtEvent<?>
    variationEvent) {
    super.onPhysicalAssetPropertyVariation(variationEvent);
    switch (variationEvent.getPhysicalPropertyId()) {
        case "heartRate": {
            int value = (Integer) variationEvent.getBody();
            healthInformation.addRegisteredBPM(
                variationEvent.getCreationTimestamp(), value);
            try {
                checkPatientHealth();
                this.digitalTwinStateManager.notifyDigitalTwinStateEvent(new
                    DigitalTwinStateEventNotification<>(NEW_HEART_RATE, value,
                    UtilsFunctions.getCurrentTimestamp()));
            } catch (...) {
                ... // error management
            }
        }
        ...
    }
}

private void checkPatientHealth() throws ... {
    List<Integer> bpms = healthInformation.getLastValues();
    int sum = 0;
    for(int i : bpms) {
```

```java
        sum += i;
    }
    double mean = (double) sum / (long) bpms.size();
    if(mean < 50 || mean > 110) {
        this.digitalTwinStateManager.notifyDigitalTwinStateEvent(new
            DigitalTwinStateEventNotification<>(MqttPatientDigitalAdapter.BPM_ANOMALY,
            mean, Utilis.getTimestamp()));
    }
}
```

Listing 5.5: Example of heart rate variation for PatientDT

Within the shadowing process also events generated by the physical asset are managed, using a specific method for handling incoming notifications from the physical layer. This method receives events propagated by the physical adapter and triggers the corresponding updates to the internal state of the twin.

Beyond state updates, the event management process also supports the dynamic handling of relationships associated with specific events. For instance, when a new surgery procedure is requested for a patient, the shadowing process can create and update the relationship between the Patient Digital Twin and the corresponding Surgery Digital Twin instance, as we can see in the following code portion (listing 5.6).

```java
@Override
protected void
    onPhysicalAssetEventNotification(PhysicalAssetEventWldtEvent<?> event) {
    if(Objects.equals(event.getPhysicalEventKey(),
        MqttPatientPhysicalAdapterBuilder.SURGERY_REQUEST)) {
        try {
            this.digitalTwinStateManager.startStateTransaction();
            SurgeryMetadata surgery = (SurgeryMetadata)event.getBody();
            Map<String, Object> relationshipMetadata = new HashMap<>();
            relationshipMetadata.put("uri", surgery.uri());
            relationshipMetadata.put("id", surgery.id());

            PhysicalAssetRelationshipInstance<String> relInstance =
                this.subjectedToRelationship.createRelationshipInstance(surgery.id());
```

```
            this.digitalTwinStateManager.addRelationshipInstance(new
                DigitalTwinStateRelationshipInstance<>(relInstance.getRelationship().getName(
                relInstance.getTargetId(), relInstance.getKey(),
                relationshipMetadata));
            this.digitalTwinStateManager.commitStateTransaction();
        } catch (WldtDigitalTwinStateException e) {
            ...
        }
    }
}
```

Listing 5.6: Example of event listening for PatientDT

5.2.3 Digital Adapters

Finally, digital adapters enable interaction between Digital Twins and the digital application layer by providing standardized mechanisms to query the state of a DT using HTTP protocol and subscribe to its event notifications using MQTT protocol, such as the heart rate anomaly notification. In particular, the *HTTP Digital Adapter* component offers defined APIs, such as:

- GET /state/properties: retrieves the current value of each property

- GET /state/events: retrieves the events list of the DT

- POST /state/actions/actionKey: triggers the specified action in the Digital Twin state, with body containing the action payload

Digital Twin composition

In addition, digital adapters support the implementation of the composition pattern between Digital Twins. Through this mechanism, a Digital Twin can act as the physical asset of another Digital Twin, enabling hierarchical and interconnected models. For example, the Vital Sign Monitor Digital Twin can provide heart rate measurements that are consumed by the Patient Digital Twin, effectively treating the monitor as a data source for the patient's physiological state (listing 5.7).

```java
@Override
protected void onStateUpdate(DigitalTwinState state, DigitalTwinState state1,
    ArrayList<DigitalTwinStateChange> changes) {
    List<DigitalTwinStateProperty<?>> changedProperties = changes.stream()
            .filter(i -> i.getResourceType() ==
                DigitalTwinStateChange.ResourceType.PROPERTY)
            .map(i -> (DigitalTwinStateProperty<?>)i.getResource())
            .filter(i ->
                getConfiguration().getObservedProperties().contains(i.getKey()))
            .collect(Collectors.toList());

    for(DigitalTwinStateProperty<?> property : changedProperties) {
        try {
            if(state.getPropertyList().isPresent()) {
                List<DigitalTwinStateProperty<?>> list =
                    state.getPropertyList().get();
                Optional<DigitalTwinStateProperty<?>> patientId =
                    list.stream().filter(i ->
                    i.getKey().equals(VSM_PATIENT_ID)).filter(i -> i.getValue()
                    != "").findFirst();
                patientId.ifPresent(digitalTwinStateProperty ->
                    publishUpdate("anylogic/id/Patient/" +
                    digitalTwinStateProperty.getValue().toString() + "/" +
                    property.getKey(), property.getValue().toString()));
            }
        } catch (WldtDigitalTwinStatePropertyException e) {
            ...
        }
    }
}
```

Listing 5.7: VSM DT sends heart rate update to associated PatientDT

5.3 KPI Elaboration

The SurgeryDT and SurgeryDepartmentDT are also responsible for computing Key Performance Indicators, to evaluate the performance of surgical activities and support operating rooms optimization. These KPIs are divided into two main categories: surgery-related KPIs and operating room–related KPIs, as we seen in preivous chapters.

Surgery KPIs focus on specific characteristics of surgical procedures and are associated with particular categories of surgeries. They provide insights into aspects for surgery journey and are calculated in the SurgeryDT every time an event update occurs or the surgical procedure ends.

Operating room KPIs, instead, evaluate the performance of the operating rooms during surgical activities, describing how effectively operating rooms are utilized, measuring aspects such as occupancy and rate of utilization, and are calculated into SurgeryDepartmentDT when the operating day ends.

5.4 HWoDT Layer

The HWoDT layer is implemented using the HWoDT framework, that creates an aggregation of DTs semantic information to be obtained from the application level exploiting web-based technologies, such as HTTP and semantic ontologies. The communication between agents and HWoDT service is made with specific adapters (listing 5.8) that convert the internal DT state into a semantic form, continuously updating every time a state change occurs.

5.4.1 FHIR representation

Digital Twins' internal state are converted into a semantic form using specific classes that implements *DigitalTwinSemantics* interface, providing a simple way to structure all properties and relationships into a FHIR semantic formalization, mapping every element of interest into FHIR resources. In this way, the HWoDT serves a dual purpose: aggregating DTs information to create an ecosystem layer and supporting the integration of DTs with different healthcare facilities, adhering to the most important health information representation standard.

```
WoDTDigitalAdapter woDTDigitalAdapter = new WoDTDigitalAdapter(
    "patient-dt-adapter",
    new WoDTDigitalAdapterConfiguration(
            URI.create("http://" + GlobalValues.WODT_DT_BASE_HOST + ":" +
                wodtPortNumber),
            new DTVersion(1, 0, 0),
            new PatientSemantic(),
            wodtPortNumber,
            "patient-" + idDT + "-" + connectionConfig.getPort(),
            Set.of(URI.create("http://localhost:4000"))
    )
);
```

Listing 5.8: Example of PatientDT HWoDT adapter, with PatientSemantic conversion class

5.4.2 SPARQL

The HWoDT layer supports data access and interoperability through the adoption of SPARQL, the semantic query language standardized by the W3C. SPARQL enables structured queries over the Digital Twins' knowledge representation, allowing applications to retrieve the current state of DTs, inspect their properties, and explore the relationships established among them, as we can see in the following example of retrieving patient information (listing 5.9).

```
PREFIX fhir: <http://www.hl7.org/fhir/>
PREFIX mao: <https://purl.org/mao/onto/>

SELECT ?patient ?name ?gender ?birthDate
WHERE {
    ?patient a fhir:Patient;
    fhir:name ?completeName;
    fhir:identifier ?identifier;
    fhir:gender ?gender;
    fhir:birthDate ?birthDate .
```

```
    ?identifier fhir:value ?identifierValue.
    ?identifierValue fhir:v '%s'.


    ?completeName fhir:given ?nameObject.
    ?nameObject fhir:v ?name.
}
```

Listing 5.9: Example of patient semantic information retrieval

5.5 Application layer dashboard

For the application level, a dashboard was created using *VueJS*, which offers an excellent modular client development framework, implementing the following features:

- Showing all the currently available digital twins, with its own details and properties

- Retrieve data from digital twins using their digital adapters and public APIs

- Retrieve aggregated data from the HWoDT platform using the knowledge graph and public APIs

- Showing aggregated data and KPIs from digital twins and HWoDT platform

- Creating an intuitive visualization of information and KPI charts

This was possible through an ad hoc developed microservice using *Spring framework*, that works as a gateway that aggregates information from Digital Twins (through their digital adapters) and the HWoDT platform to retrieve higher-level information about the ecosystem, displaying the various KPIs in graphical and numerical form in a simple and intuitive way to understand the current status and performance of the operating block.

Chapter 6

Testing and validation

The design and development of the software was carried out simultaneously with the testing of the features as they were produced, in order to ensure its correctness, reliability, and consistency with the intended design. The validation process was conducted through a combination of unit testing and manual evaluation based on predefined simulation scenarios, because of the strong relationship between Digital Twins and physical assets behavior.

6.1   Unit testing

Unit tests, developed using the JUnit framework, were a key component in testing the KPI calculations in various predefined scenarios. This was done to ensure that the values generated by the Digital Twins during a specific scenario were correct before applying the DT ecosystem over the actual simulation. The scenarios were created by defining specific lists of interventions to be performed, time slots for each operating room, and a set of pre-recorded events with their corresponding timestamps.

6.2   Shadowing testing and evaluation

Regarding testing the Digital Twin shadowing, manual tests were performed using both physical and digital adapters to validate the correctness and effectiveness of mirroring. The effectiveness of mirroring properties and events was tested using MQTT, specifically

using tools like *MQTT Explorer* to publish/subscribe to the digital twins channels. For actions and relationships, *Postman* was used to obtain the current state of the digital twins and invoke actions, simulating a digital application or sending an action from a physical asset.

6.3   Digital Twins validation

The final phase of the project focused on the testing and validation of the proposed system to ensure its correctness and consistency with the intended design and requirements. The AnyLogic simulation environment (fig. 6.1) was also used as a validation tool to assess the correctness and consistency of the digital twin layer. By using the simulation as a controlled representation of the physical environment, it was possible to verify that each digital twin correctly reflected the state of its corresponding asset, properly managed events, and maintained coherent relationships with other digital twins. The validation focused on evaluating the correct execution of the shadowing process, the expected behaviors of digital twins in response to simulated events, and the reliability of the generated results, such as state updates and KPI calculations. Comparing the simulated system evolution with the corresponding digital twin responses allowed the identification of inconsistencies and ensured that the implemented models accurately reproduced the intended behaviors and interactions within the peri-operative process.
The simulation was tested using the tools made available by AnyLogic, such as the Logic panel for debugging the perioperative process (fig. 6.2) and the Parameters panel for dynamically changing custom parameters and evaluating the status of certain values.

6.3.1   Semantic validation with Protegé and SPARQL

To carry out checks and validations of the semantic representations of the Digital Twins, the Ontograf tool by Protegé was used, which allows to connect to the HWoDT platform and view the entire knowledge graph of the Digital Twins, with the possibility of easily navigating between the created instances and all the FHIR semantic properties and relationships (fig. 6.3).
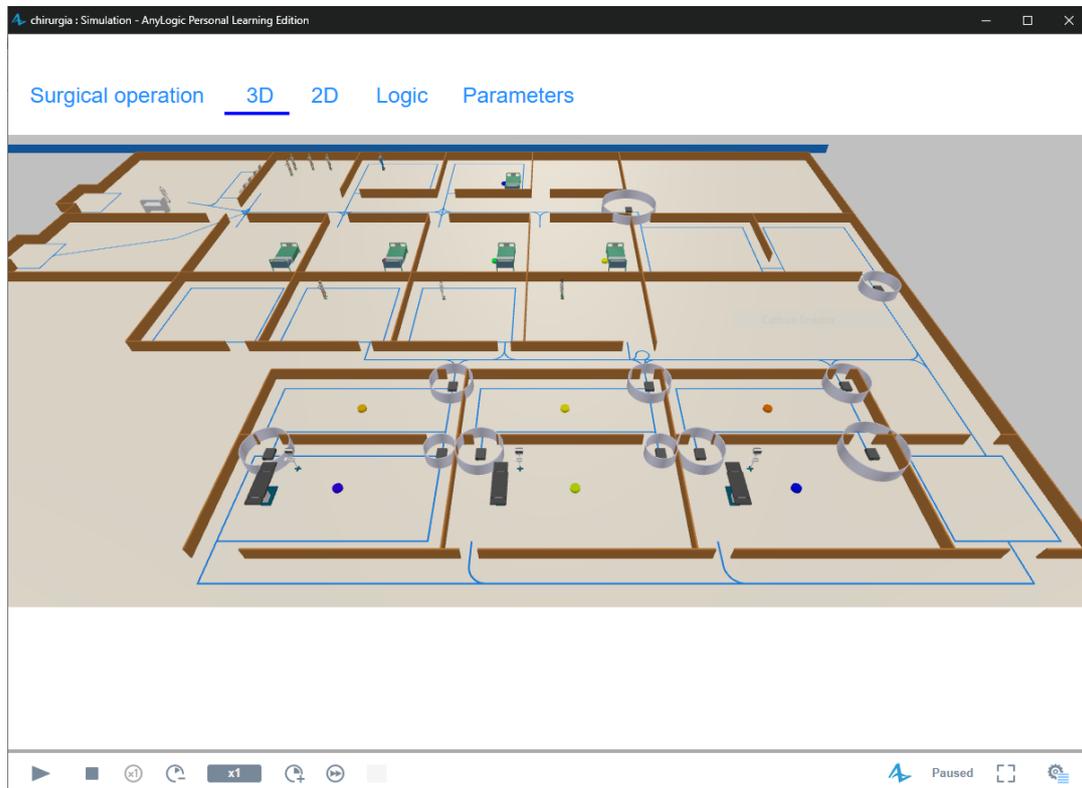
Figure 6.1: Running simulation screenshot

6.3.2 KPI visualization

The visualization and analysis of KPIs are enabled through an ad hoc microservice that acts as a gateway between the client dashboard, the HWoDT platform, and the underlying digital twins. This microservice is responsible for querying the KPIs stored within individual Digital Twins, aggregating different information and computing additional high-level indicators at the ecosystem level through the HWoDT layer, such as information about waiting list consistency and over-threshold patients. In addition to KPI aggregation, the microservice allows real-time monitoring of the physical assets through their digital twins, enabling the dashboard to display information such as ongoing surgeries, patient locations across the surgical department and operating room availability or status (fig. 6.4). This approach provides a comprehensive and dynamic view of the surgical department's performance and real-time monitoring of the actual department state.
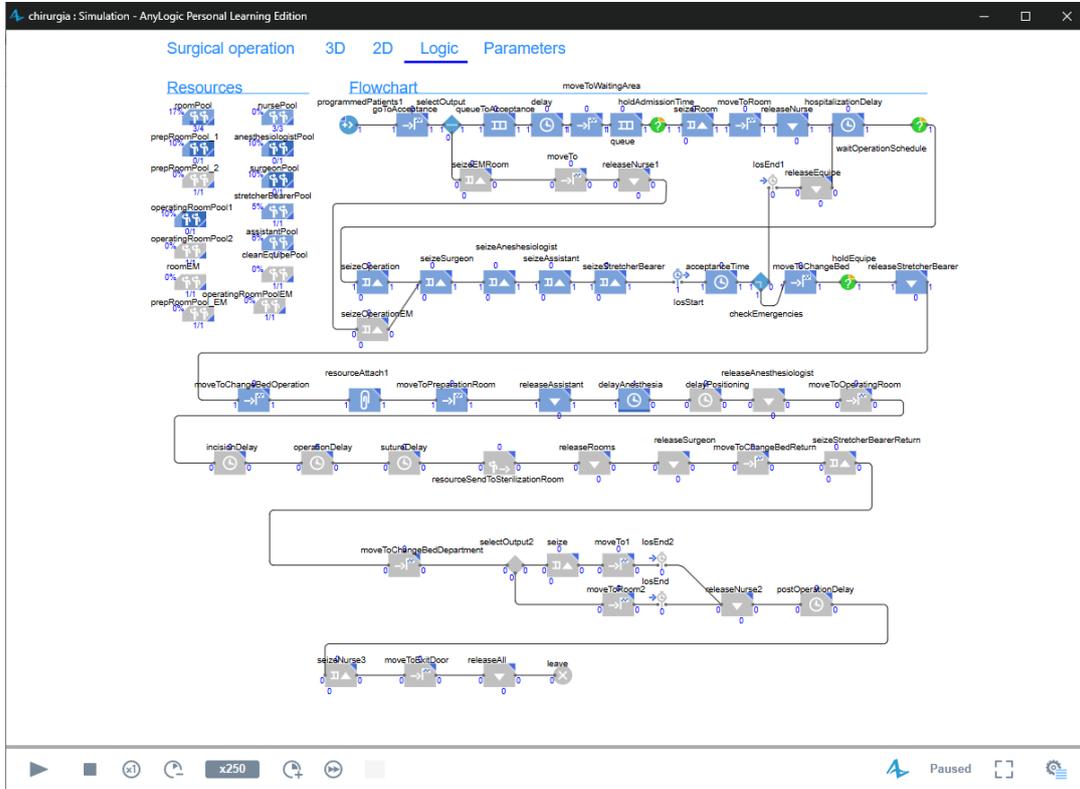
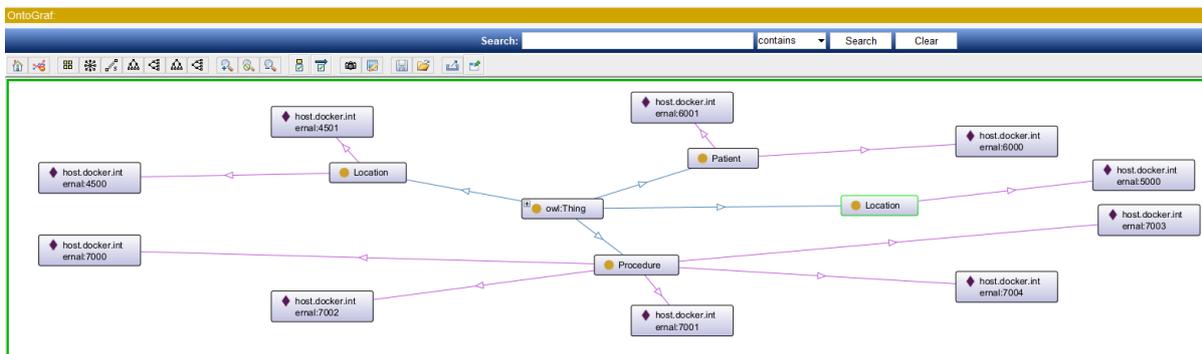119

Figure 6.2: Simulation execution logic screenshot

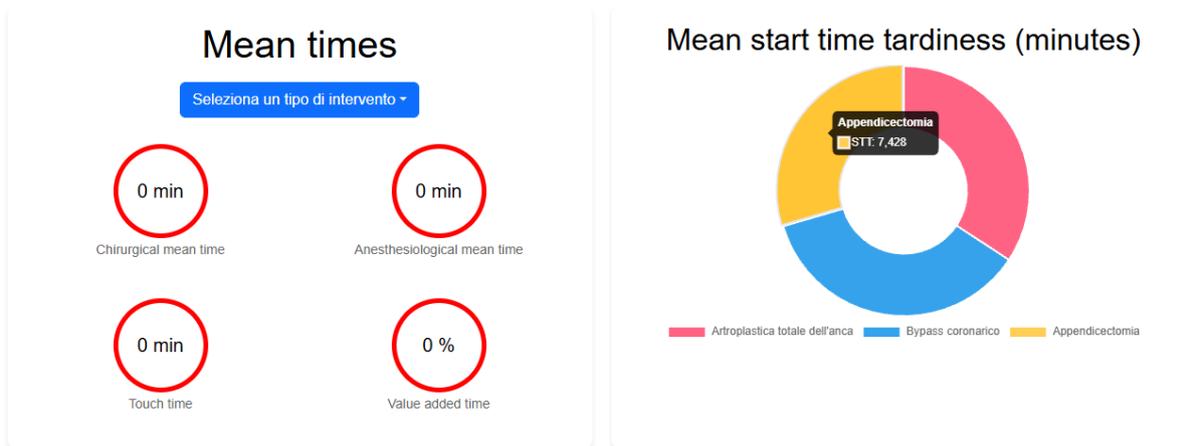Figure 6.3: Protegé Ontograf visualization of Digital Twins

Figure 6.4: Example of a dashboard view showing surgeries KPIs

Chapter 7

Conclusions

The project's initial goal was to demonstrate how the application of Digital Twins within a hospital, and more generally in the healthcare sector, can bring numerous tangible and concrete benefits immediately if supported by an appropriate technological structure within the hospital context. I believe the objectives have been fully achieved, despite the complexity of the hospital context and the dynamics that characterize every aspect of it. This project made me realize how crucial it is to have an adequate level of cutting-edge technology in healthcare, both to offer better patient service and to ensure the best working conditions for medical staff, thus facilitating and improving the management of the most critical area of a hospital: the operating rooms department. This also made me reflect on how useful the application of technologies like Digital Twins in general is in any context, even more so when built with an agent-oriented approach, unlocking new opportunities for innovation. The next step would be to apply the system in a real hospital context, in order to better evaluate the potential of digital twins and bring real benefits within the physical hospital: research of new frontiers must not be an end in itself, but lead to real improvement, to change the world.

7.1 Future improvements

Several future improvements can further enhance the proposed Digital Twin ecosystem for the surgical department. For example, using digital twins and agent-based systems to implement an automatic surgical intervention planner, knowing the waiting lists and

the various interventions to be scheduled and performed. The introduction of just-in-time Digital Twins for emergency surgeries could extend the monitoring capabilities to unplanned and high-priority procedures, increasing the completeness of the ecosystem. Additionally, advanced analytics and machine learning techniques could be incorporated to move from descriptive KPI analysis to predictive and prescriptive decision support, such as forecasting operating room congestion, estimating surgery delays, or optimizing resource allocation dynamically. Finally, the implementation of enhanced security mechanisms and role-based access control would strengthen data governance, ensuring compliance with healthcare regulations while supporting scalable adoption in complex hospital environments.

To my mother and my family.

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