

Enterprise Architecture for Model-Driven Clinical Operations Management in Value-Based Hospitals

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Abstract

Value-based hospital is a concept that is causing a major transformation of hospitals and their information systems. Currently, hospitals are organized by medical units and by specialties that tend to operate as separate silos, without much communication between them. The transitions of care are not optimal for the patients, thus negatively impacting patient outcomes. Value-based hospitals focus on groups of patients with similar conditions, and end-to-end care pathways like Hip & Knee Replacement. They organize service lines that provide end-to-end care for these patient groups through the Emergency Department, Diagnostic Imaging, Lab tests, the surgical procedure in the Operating Room, the stay in the Surgery unit, Rehabilitation, and then discharge from the hospital. To enact such a transformation, hospitals have to redesign their Clinical Operations Management (care processes and organization) and the supporting information systems.

Enterprise Architecture is the discipline, defined by international standards bodies, which concerns itself with transformational change of large complex organizations supported by information technology. Model-Driven Engineering is an approach to designing and generating information systems based on models. This thesis proposes an Enterprise Architecture for Model-Driven Clinical Operations Management (COM) to address the required transformation and improvement of clinical information systems to support value-based hospitals.

The first thesis contribution is an Enterprise Architecture for Model-Driven COM in value-based hospitals, including COM Models, UML/BPMN/DMN Models, an Architecture and Design for a Clinical Operations Support System (COSS) for COM, and four COM Diagrams and Templates. The COM Models are the Business Architecture of the Enterprise Architecture; they are the foundation of our model-driven transformation approach. The UML/BPMN/DMN Models are derived from the COM Models, and are the Information System Architecture of the Enterprise Architecture. The COSS for COM, generated from the above models, is the Technology Architecture of the Enterprise

Architecture. Finally, the COM Diagrams and Templates enable to better communicate the Enterprise Architecture; they are the COM Functions Table, the COM Enterprise Architecture Diagram, the COM Service Line Template, and the COSS Architecture Diagram.

A second thesis contribution is the design of two domain-specific model-driven tools, based on the Eclipse environment, which support the design and generation of information systems support of COM in a value-based hospital. The COMP Tools include a Modeling Tool for COM based on a COM Functions Table for Hospitals, a Domain-Specific Modeling Language for COM (COMP: the COM Profile), and its Meta Model. The COSBench software development workbench provides support to the Model-Driven Engineering of information systems for COM.

Finally, a third contribution is examples of COM Models for Joint Replacement service line and for Cardiac Procedures service line, used in our case studies to illustrate and validate the approach. There are also examples of COSS Decision Support Systems for patient flow management, operational business intelligence, full-capacity protocol, demand management, and capacity management.

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As opposed to most students completing a PhD, I am not at the beginning of my career now. It was a personal goal of mine to close this 37-year loop that started on a university campus in the Silicon Valley, and brought my family and me to France, England, and Canada, with a thesis which could be somehow useful to Ontario hospitals. The Health System Funding Reform is an excellent opportunity for our hospitals to transform themselves for the better, but it also presents a formidable challenge. A maxim reputedly attributed to Michelangelo while painting the ceiling of the Sistine Chapel, comes to mind: “The greater danger for most Ontario hospitals lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark.”. My hope is that Ontario hospitals dare to aim high; our patients need and deserve it.

Alain Mouttham

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List of Acronyms

ACS. *Acute Coronary Syndrome*

AM. *Accounting Management*

BI. *Business Intelligence*

BPM. *Business Process Management*

BPMN. *Business Process Model and Notation*

CEP. *Complex Event Processing*

CHF. *Congestive Heart Failure*

CHOIR. *uTwente Center for Healthcare Operations Improvement & Research*

CIM. *Computing Independent Model*

COM. *Clinical Operations Management*

COMF. *Clinical Operations Management Functions Table*

COMP. *Clinical Operations Management Profile*

COOM. *Clinical Operations Object Model*

COPD. *Chronic Obstructive Pulmonary Disease*

COSS. *Clinical Operations Support System*

DCM. *Demand Capacity Management*

DMN. *Decision Model and Notation*

EA. *Enterprise Architecture*

ED. *Emergency Department*

EDA. *Event-Driven Architecture*

EHR. *Electronic Health Record*

EMF. *Eclipse Modeling Framework*

EMR. *Electronic Medical Record*

HiMSS. *Healthcare Information Management Systems Society*

HRM. *Human Resources Management*

IOM. *Institute of Medicine*

IS. *Information System*

MCDA. *Multi-Criteria Decision Analysis*

MDA. *Model-Driven Architecture*

MDE. *Model-Driven Engineering*

MOHLTC. *Ministry of Health and Long-Term Care*

OMG. *Object Management Group*

OR. *Operating Room*

PFM. *Patient Flow Management*

PIM. *Platform Independent Model*

PM. *Performance Management*

PSM. *Platform Specific Model*

QoC. *Quality of Care*

QoCM. *Quality of Care, Risk & Safety Management*

RTDC. *Real-Time Demand Capacity*

RTLS. *Real-Time Location System*

SLM. *Service Line Management*

SM. *Supply Management*

SOA. *Service-Oriented Architecture*

SOAML. *Service-Oriented Architecture Modeling Language*

TOGAF. *The Open Group Architecture Forum*

UML. *Unified Modeling Language*

1 Introduction

1.1 Problem Statement

Healthcare systems across the world are undergoing a big transformation similar in scope and ambition to what happened in the telecommunications industry some 20 years ago. The traditional system, starting at the hospital, is “fee-for-service”; this means that funding is based on the volume of care delivered to patients. The new system is value-based, meaning that funding is based on the outcomes of the care and its end-to-end value for the patient. The transformation of “fee-for-service” hospitals towards value-based hospitals has a significant impact on all aspects of operations.

Currently, hospitals are organized along medical disciplines and activities. The units such as the Emergency Department, the General Medicine wards, the Operating Rooms and Surgery wards are working in silos, with minimum interaction between them. This is sometimes called the “vertical organization”. In a value-based hospital, the funding is provided for the end-to-end care of a group of patients with similar conditions (for instance, Hip & Knee Replacement, Congestive Heart Failure, or Heart Attack), based on the outcomes of care. This will drive towards a “horizontal organization” of hospitals, along the lines of patient groups and disease groups. This horizontal organization must be integrated because the funding will be provided for a bundle of care including, for instance in the case of a Hip Fracture patient, the stay in the ED, the OR, the Surgery ward, and finally the Rehabilitation. This will require more and better collaboration between units.

As described in section 2.2, several European countries have started the journey towards Value-Based Care. In the US, the Accountable Care Act is the embodiment of Value-Based Care. In Canada, the Ontario Health System Funding Reform has also triggered such transformation.

A hospital undertaking a transformation of such magnitude will have to redesign its care processes and organization, that is its Clinical Operations Management, and the information systems supporting it [Hanna2005]. Enterprise Architecture is the discipline, defined by international standards bodies, which concerns itself with transformational change of large complex organizations supported by information technology [TOGAF9]. Major transformations have happened in other industries before; however here, the challenge is compounded by the fact that healthcare is acknowledged as one of the most complex industries, with a lot of inherent uncertainties in its operations. To make matters worse, the Institute of Medicine has released a report “Better care at Lower cost” [IOM2012] stating that Healthcare has not progressed as much as other industries in the use of information technology to support the transformation. Other sources assess the lag to between 10 and 20 years [NHS2009].

Therefore, to support the transformation towards value-based hospital, our research proposes an Enterprise Architecture for Model-Driven Clinical Operations Management to address the required improvements to clinical information systems to support value-based hospitals. In other industries like the automobile or telecommunications, model-driven transformation has proven to be useful. Is this also true for Healthcare, and how could we achieve this?

1.2 Motivation

The domain for this thesis is Health Informatics applied to Clinical Operations Management (COM) in Hospitals. The thesis, and the theory developed throughout, is at the intersection of 3 academic disciplines: Clinical Care, Computer Science, and Healthcare Administration (including Operations Management).

In order to understand how a hospital works, what their information technology needs are to support the transformation, and what realistically can be done when local culture is taken into consideration, I have followed the Design Science Research method

[Hevner2004, Hevner2010] combined with Action Research [Baskerville1999] and spent 6 years embedded in 3 Ontario hospitals:

- Osler (2010-2013): Cardiology and Emergency Department
- Queensway-Carleton (2013-2015): Emergency Department, Internal Medicine, Surgery and Peri-Operative
- Montfort (2015-now): Surgery, Medicine

The theory which emerged from the observations and experiments conducted in the hospitals is that a model-driven transformation, with the models being defined by the clinicians themselves to generate customized information systems, could be an effective solution.

The current information systems addressing this domain are point products which are not aligned with clinician workflows, are not real-time, are not end-to-end, and are not as patient-centered as they should be, and are not as customizable for each hospital as they could be.

1.3 Theory, Research Question, and Hypotheses

The underlying premise of our thesis is that, in the context of hospital transformation to become value-based, organizational and process redesign have to be supported by a redesign of information systems for Clinical Operations Management (COM). These COM information systems should be customizable for each hospital, end-to-end, real-time, patient-centered, and aligned with clinician workflows. The transformation is best achieved with a model-driven COM approach, and we are focusing on its Enterprise Architecture.

Validating this theory in its entirety is beyond the scope of this thesis. Instead, we are focused on a research question addressing a subset of the theory, as shown in the figure below.

Research Question: Can we use Model-Driven Engineering to provide better Information System support for COM in a value-based hospital, with a coverage of clinical services that is customizable for each hospital, end-to-end, real-time, patient-centered, aligned with the clinician workflows, and based on models defined by the Clinicians themselves? What would an Enterprise Architecture for Model-Driven COM in value-based hospitals be?

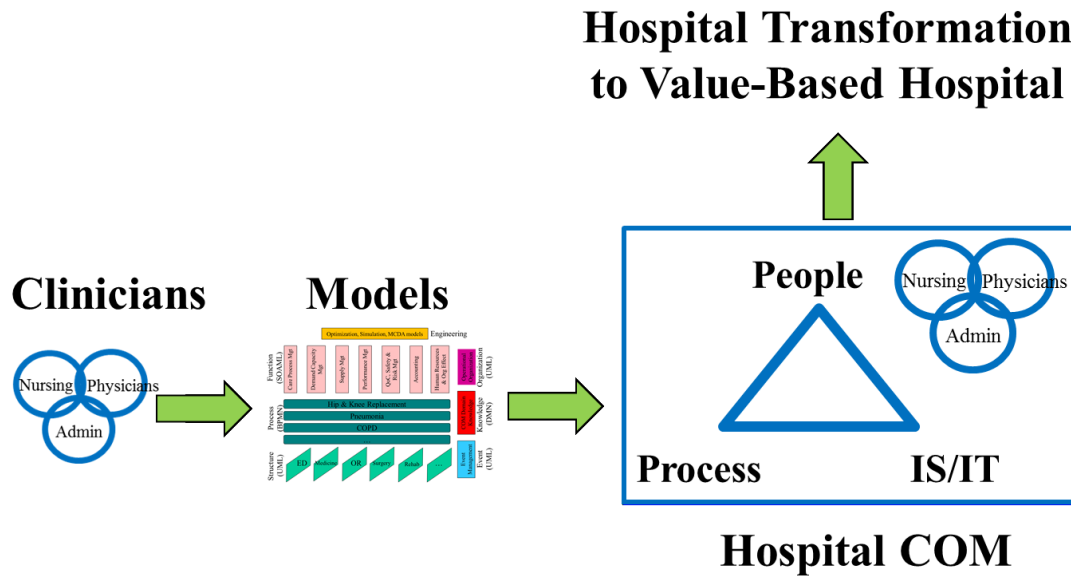


Figure 1-1 Model-Driven Engineering of COM in value-based hospitals

In addressing this research question, the thesis will attempt to validate the following hypotheses:

- H1: Using Model-Driven Engineering, there is an effective way to build models for COM in a value-based hospital, which drives the development of customized information systems for end-to-end, real-time, patient-centered clinical service management, in alignment with clinician workflows. We validate this hypothesis with case studies that focus on COM for Cardiac patient flows, and for Hip & Knee Replacement Service Line.
- H2: Using a Blackboard Architectural Pattern, there is an effective way to build model-based Decision Support Services for COM in a value-based hospital. We

validate this hypothesis with case studies that focus on COM for patient flows in the context of “surge”, where sudden increased demand for services often results in unacceptably long wait times.

- H3: Clinicians, with help from Health Informatics analysts, and with appropriate training and tools, can define the models used in H1 and H2. We validate this through our work with clinicians in our case studies.
- H4: The information systems created by our approach provide better support to COM for value-based hospitals compared to the current practice. We validate this hypothesis with case studies for cardiac patient flow management and for Hip & Knee Replacement Service Line.

1.4 Methodology

Our research methodology is primarily Design Science Research in Information Systems [Hevner2004, Hevner2010] which is an iterative cycle of analysis, hypothesis, design, prototyping, and validation of outcomes that can lead to new hypotheses and designs. Figure 1-2 Design Science Research [Hevner2004, Hevner2010] below shows the essential guidelines.

Table 1. Design-Science Research Guidelines	
Guideline	Description
Guideline 1: Design as an Artifact	Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation.
Guideline 2: Problem Relevance	The objective of design-science research is to develop technology-based solutions to important and relevant business problems.
Guideline 3: Design Evaluation	The utility, quality, and efficacy of a design artifact must be rigorously demonstrated via well-executed evaluation methods.
Guideline 4: Research Contributions	Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and/or design methodologies.
Guideline 5: Research Rigor	Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact.
Guideline 6: Design as a Search Process	The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment.
Guideline 7: Communication of Research	Design-science research must be presented effectively both to technology-oriented as well as management-oriented audiences.

Figure 1-2 Design Science Research [Hevner2004, Hevner2010]

There are 3 Design Science Research cycles:

- The Relevance Cycle identifies the environment providing the requirements for the research as inputs, and the acceptance criteria for the evaluation of the research results. This ensures that the research on information systems remains at all times relevant to the people, organization, and technology contexts
- The Rigor Cycle provides past knowledge from the literature to the research project to support its innovation, and ensures that additions to the literature as results of the research project will include additions/extensions to the original theories/methodologies, new artifacts (design products and processes), and all experience gained.
- The Design Cycle provides the rapid iteration between the construction of an artifact (the research prototype), its evaluation, and subsequent feedback to refine the design further.

We have combined Design Science Research methodology with Action Research methodology in our thesis work, in particular to ground our relevance cycle in the actual

experience of hospitals and clinicians working to address real problems [Jarvinen2005]. The goal of Action Research [Baskerville1999] is to facilitate the enunciation and validation of research by moving from the “lab” to the “field”. It is based on in-situ observation, analysis, and experimentation. It identifies three specific and different roles for the researcher [Wieringa2012]:

- Consultant or Helper: to help address real problems in the environment
- Researcher: to increase knowledge in the literature
- Designer or Engineer: to design and develop artifacts which address real problems and contribute to research

These roles are likely to bring conflicting priorities, and the researcher must keep these roles separate with clear and differentiated priorities.

Here in detail is our combined use of Design Science Research and Action Research methodology. Following the Design Science Research (DSR) for Information Systems, we focused on designing Artifacts in a given Context which produce Effects by some described Mechanisms:

- The Context is Clinical Operations Management (COM) in Ontario Hospitals.
- The Artifacts are a set of modeling tools for the design of the models; two sets of domain-specific models; a software development workbench for the model-driven generation of an information system for COM; and finally, the generated domain-specific information system itself.
- The Mechanism is the Model-Driven Engineering approach.
- The Effect is the generation of the customized, end-to-end, patient-centric, real-time information system for COM in the hospital, which is aligned with Clinician workflows.

Action Research provided a natural path from lab work to field work. The Theory was articulated based on observations, analysis, and experimentation in hospitals; it led to the definition of the Research Question. Then, the Design started in the university lab and the

artifacts were validated in the hospitals later on. This was conducted over a period of 6 years at 3 Ontario hospitals.

1.5 Thesis Contribution

1.5.1 COM Platform

We have annotated Figure 1-1 Model-Driven Engineering of COM in value-based hospitals to show where our thesis makes contributions (in red) to the Model-Driven COM in hospitals. See Figure 1-3 Thesis Contributions below.

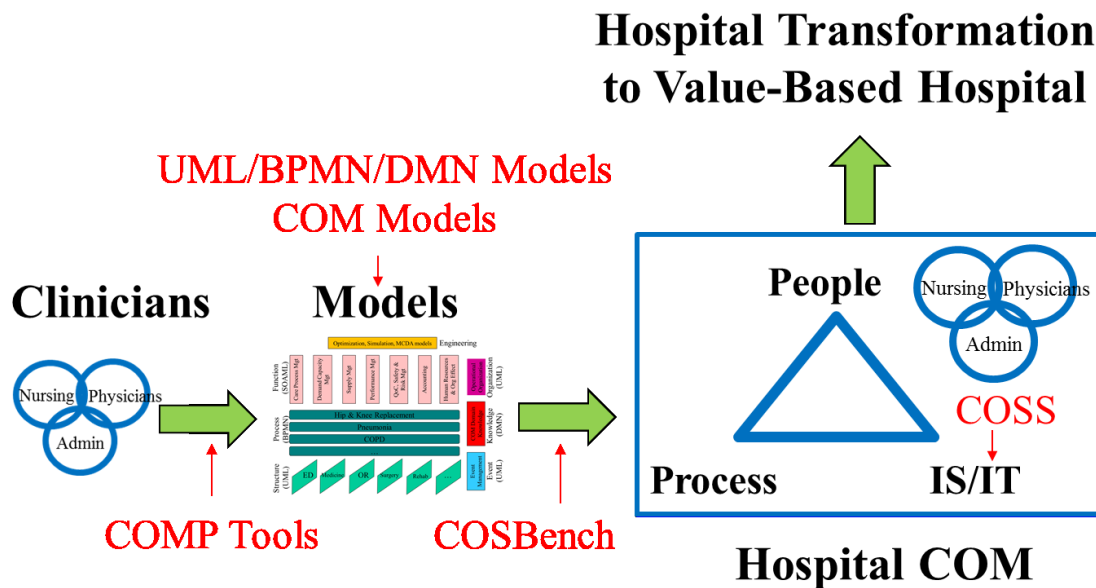


Figure 1-3 Thesis Contributions

Per the Design Science Research methodology, the Artifacts themselves are a contribution to Knowledge. We have built a COM Platform.

A first contribution is an Enterprise Architecture (EA) for Model-Driven COM in Value-Based Hospitals:

- COM Models - Specification of a set of COM Models which are the Business Architecture of an Enterprise Architecture for the Model-Driven COM in value-

based hospitals. They are the foundation of our Model-Driven Transformation approach.

- UML/BPMN/DMN Models – These models are derived from the COM Models, and are the IS Architecture of an Enterprise Architecture for the Model-Driven Transformation of hospitals.
- COSS Architecture and Design - An information system for COM, called Clinical Operations Support System (COSS), which provides amongst other things, decision support systems, using Model-Based Reasoning, and more specifically the Blackboard Architectural Pattern. This is the Technology Architecture of an Enterprise Architecture for the Model-Driven Transformation of hospitals. The COSS is generated from the UML/BPMN/DMN models.
- COM Diagrams and Templates – We have defined the following specific types of diagrams and templates to better communicate COM Enterprise Architecture:
 - COM Functions Table
 - COM Enterprise Architecture Diagram
 - COM Service Line Template
 - COSS Architecture Diagram

A second thesis contribution is the design of a set of domain-specific tools, based on the Eclipse environment, which support the Model-Driven COM in Value-Based Hospitals:

- COMP Tools - Definition, architecture and design of a Modeling Tool for COM (COMP Modeling Tool), based on a COM Functions Table (COMF) for Hospitals, a Domain-Specific Modeling Language for COM (COMP), and its Meta Model.
- COSBench – Definition, architecture and design of a software development workbench (COSBench) to support Model-Driven Engineering of information systems for COM.

Finally, a third contribution is examples of COM Models for Joint Replacement service line and for Cardiac Procedures service line, used in our case studies to illustrate and validate the approach. There are also design examples of COSS Decision Support

Systems for patient flow management, operational business intelligence, full-capacity protocol, demand management, and capacity management.

1.5.2 Published papers related to this Thesis

- M Baslyman, R Rezaee, D Amyot, A Mouttham, R Chreyh, G Geiger, A Stewart, S Sader “Real-Time and location-based hand hygiene monitoring and notification: proof-of-concept system and experimentation” Journal of Personal and Ubiquitous Computing Vol 19 Issue 3-4 July 2015
- M Baslyman, R Rezaee, D Amyot, A Mouttham, R Chreyh, G Geiger “Towards an RTLS-based Hand Hygiene Notification System” The 4th International Conference on Current and Future Trends of Information & Communication Technology in Healthcare (ICTH 2014)
- R Rezaee, M Baslyman, D Amyot, A Mouttham, R Chreyh, G Geiger “ Location-based Patient-Device Association and Disassociation” The 4th International Conference on Current and Future Trends of Information & Communication Technology in Healthcare (ICTH 2014)
- RB Tchemeube, D Amyot, A Mouttham “Location-aware business process management for real-time monitoring of a cardiac care process” CASCON’13 Proceedings of the 2013 Conference of the Center for Advanced Studies on Collaborative Research
- S Bahrani, RB Tchemeube, A Mouttham, D Amyot, “Real-time Simulations to support operational decision-making in Healthcare” SCSC’13 Proceedings of the 2013 Summer Computer Simulation Conference
- L. Peyton, A. Mouttham, K.A. Ali, A. Baarah, H.T. Mouftah, Real-time Analytics and Quality of Care, Handbook on Systems and Complexity in Health. Eds. J.P. Sturmberg and C.M Martin. Springer, 2013. ISBN 978-1-4614-4997-3
- A. Mouttham, C. Kuziemy, D. Langayan, Y. Ling, L. Peyton, J. Pereira, Interoperable Support for Collaborative, Mobile, and Accessible Health Care, Journal of Information Systems Frontiers, Volume 14, Number 1, 2012, pp. 73-85

- A. Baarah, A. Mouttham, L. Peyton, Architecture of an Event Processing Application for Monitoring Cardiac Patient Wait times, International Journal of Information Technology and Web Engineering (IJITWE), 7(1), pp. 1-16, 2012. doi:10.4018/jitwe.2012010101.
- Baarah A, Mouttham A, Peyton L, Improving Cardiac Patient Flow Based On Complex Event Processing, 2011 IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies, Amman, Jordan, December 2011
- Mouttham A, Peyton L, Kuziemy C, Leveraging Performance Analytics to Improve Integration of Care, Software Engineering in Healthcare 2011, Hawaii, US, May, 2011.
- B. Eze, C. Kuziemy, L. Peyton, G. Middleton, A. Mouttham, Policy-based Data Integration for e-Health Monitoring Processes in a B2B Environment, Journal of Theoretical and Applied Electronic Commerce Research, Vol. 5, No. 1, pp 56-70, 2010.
- Mouttham A, Peyton L, Eze B, El Saddik A, Event-Driven Data Integration for Personal Health Monitoring, Journal of Emerging Technologies in Web Intelligence, Academy Publisher, Vol. 1, No 2, pp 110-118, 2009, DOI:10.4304/jetwi.1.2.110-118
- Mouttham A, Peyton L, El Saddik A, Business Process Integration and Management of next-generation Health Monitoring Systems, Workshop on eHealth System Interoperability, MCETech 2009, Ottawa, Canada, May, 2009.
- J. Silva, A. Mouttham, A. El Saddik, "UbiMeds: a mobile application to improve accessibility and support medication adherence", MSIADU '09 Proceedings of the 1st ACM SIGMM international workshop on Media studies and implementations that help improving access to disabled users, 2009

2 Background and Related Work

2.1 Clinical Operations Management (COM)

2.1.1 Operations Management in the Manufacturing Industry

The Manufacturing Industry has identified more than 30 years ago the need for computer-aided operations management [MP Groover, 1980]. The main functions are:

- Strategic Operations Management
- New product design
- Inventory Management, Supply Chain Management, Materials Management
- Planning & Control
- Quality Management
- Facilities Management

The Planning & Control function is further composed of:

- Master Scheduling
- Capacity Planning
- Scheduling of production
- Shop Floor control

2.1.2 Clinical Operations Management

In “The diffusion of Operations Management Concepts into the Healthcare Sector” [Hanna2005], the authors describe how the following operation management techniques can be applied to Healthcare: Process Flow and Capacity management, Process Design and Business Process Re-Engineering, Total Quality Management and Six Sigma, LEAN, Supply Chain Management, and Operations Strategy. The LEAN approach has been promoted by the Institute for Healthcare Improvement for many years [IHI2005]. LEAN

has been successfully applied at several hospitals [Holden2012, DeKoning2006]. In “Reengineering the Cardiac Catheterization Lab: a Lean Approach” [Raghaven2010], a detailed example is given on how to identify sources of delays in the Cardiac Catheterization Lab that lead to prolonged patient turnaround times. Ontario hospitals have applied Quality by Design [IPAC2010]. Other Operations Management tools include operational models of hospital resources [Harper2002], Capacity Planning and Management in Hospitals [Green2003], Process Integration [HFMA2003], Transformation and Change management [IHI2010].

2.1.3 Care Pathway; Quality-Based Procedure (QBP)

Care Pathways (CP) are defined from a clinical perspective, and they complement Hospital Operations Management techniques. A CP defines the clinical process, the deliverables, the roles, the task sequencing. Operations Management takes care of matching demand and services, the optimum utilization of capacity, the way clinical units use their resources. This is described in “Operations Management and Care Pathways” [Vissers2012]. CPs are suitable for 60-70% of the patient population within a defined group [QH2005]. CPs are used in the following areas [NSWDH2006]:

- High cost: for instance, hip and knee surgery
- High risk: for instance, cardio-vascular procedures
- High volume: for instance, day surgery
- High interest: for instance, mental health

The report “Integrated Healthcare in England: Lessons for Ontario” published in 2009 [TCF2009] states that the use of care pathways across the continuum of care is a critical component of performance improvement initiatives in hospitals. Other sources [Schrijvers2012, Campbell1998] describe the theories and concepts behind Care Pathways. The articles “An overview on the history and concept of care pathways as complex interventions” [Vanhaecht2010] and “Towards a formalization of Care Pathways to embody good practices in Healthcare” [Crocker2007] describe how and why

Care Pathways are going to become a critical component of performance improvement in hospitals world-wide. The UK NHS has been one of the world-leading healthcare organization to adopt care Pathways across all hospitals [NHS2006, ICPUS2007, NLIAHW2005, NHS2010].

Electronic Care Pathways bring much more value to hospitals than paper-based CPs. The lack of automation/computerization has traditionally been one of the barriers of adoption for CP [Evans-Lacko2010]. The experience of the UK and Australia on Clinical Care Re-Design has shown that Operations Management tools have to be used system-wide in order to be successful; however, one of the main obstacles is that most of these tools are paper-based. One Institute of Medicine report highlighted the very significant contribution ICT could make to Healthcare thanks to progress during the last few years, beyond EHR/EMR adoption [HiMSS-EMRAM].

Recently, Care Pathways have been computerized [Gooch2011]. The implementation challenges are summarized in “Facilitators and barriers to implementing clinical care pathways” [Evans-Lacko2010] and include:

- Complexity: impact on run-time performance
- Data mapping to EHR
- Exception handling: unplanned deviations from pathway
- Flexibility and Adaptability of the Pathway at run-time to individual patient and clinician
- Goal modeling: the intention of each task in the Pathway has to be explicit
- Separation of concerns: separation of medical knowledge from workflow (operational) knowledge that can be integrated into Pathway model at run-time
- Temporal abstraction: how to model temporal constraints and periodicity in Care Pathway

The main functions of computerized care pathways are listed in Figure 2-1 Standard Functions of electronic Clinical Pathways (eCP) [Wakamiya2009]. They are taken from “What are the standard functions of electronic Clinical Pathways?” [Wakamiya2009].

Table 2 – Proposed standard functions of eCP.	
Functions	Details
Displaying	Improving visibility of checklists (10) Switching views alternately between electronic medical or care records and eCP (11)
Recording	Computerizing records (8)
Ordering	Automated ordering of medications, examinations, or injections included in CPs (6) Entering orders including medicine guidance, nourishment guidance, and rehabilitation directly from the checklists (12) Canceling remaining scheduled orders for CPs in a batch when variance occurs (14) Adding or canceling some orders while CPs are implemented (13) Using more than two CPs at the same time (15) Using CPs adopted in part of medical care or examinations (16) Calculation of rough costs of each CP (9)
Editing	Preparing templates of items within the cells of checklists (17) Recording the history of both addition and revision of CPs (18) Editing checklists for staff and nurses (1) Editing checklists for patients (1)
Variance	Reporting variance (2) Checking the occurrence of variance (3)
Statistics	Calculating statistics of circulation of CP and viewing the list of CPs (4) Viewing reports of variance (5) Calculating statistics of variance in each CP (5) Calculating statistics of variance in each variance code (5) Calculating statistics of variance for each day that variance occurred (5) Calculating statistics of variance for each action plan (5)

Figure 2-1 Standard Functions of electronic Clinical Pathways (eCP)
[Wakamiya2009]

Quality-Based Procedure

A Quality-Based Procedure is a high-level Care Pathway, used in Ontario for benchmarking and funding the hospitals. Here is a list of QBPs released by the MOHLTC in the last 3 years [QBP]:

- Chronic Kidney Disease
- Chronic Obstructive Pulmonary Disease
- Pneumonia
- Stroke
- Congestive Heart Failure
- Coronary Artery Disease
- Aortic Valve Disease
- Hip & Knee Replacement
- Hip Fracture
- Cataract Surgery
- Cancer Surgery

Figure 2-2 Hip Fracture QBP below gives an example of QBP for Hip Fracture. It describes the Patient presenting at the Emergency Department, being assessed and medically stabilized. Then, if surgery is required, the Patient is admitted to the Surgery ward, given the pre-Op care, sent to the Operating Room [OR] for the surgical procedure, then given the post-Op care and mobilization. Finally, the patient is sent to Rehabilitation and discharged from hospital.

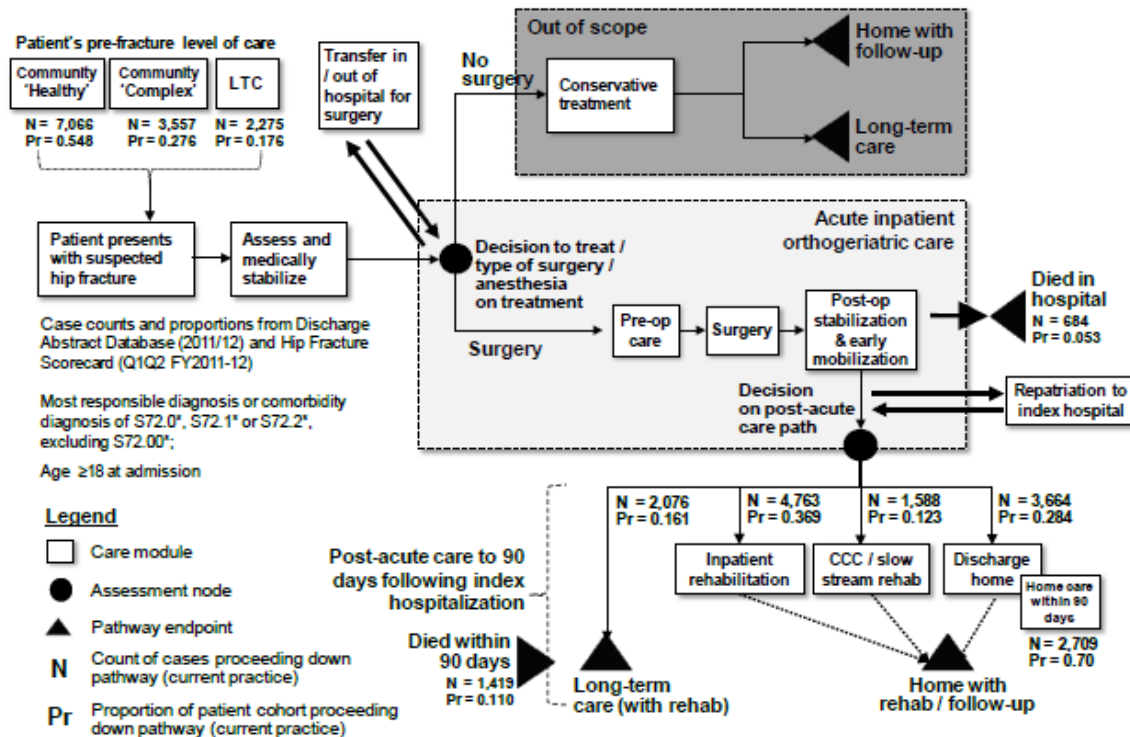


Figure 12: Episode of Care Model for Hip Fracture
Abbreviations: LTC, long-term care; CCC, complex continuing care; N, crude counts; Pr, proportions.

Figure 2-2 Hip Fracture QBP

We are using the QBP for Coronary Artery Disease and for Hip & Knee Replacement in the case studies of sections 5.2 and 5.3, respectively.

2.1.4 Patient Flow Management (PFM)

A major sub-domain of Clinical Operations Management is Patient Flow Management (PFM), in which patient flow through defined care pathways is managed. PFM is a system-wide primary process [AccreditationCanada2012]. The best way to handle Patient Flow problems is to consider them across the entire continuum of care, end-to-end.

One lesson from the UK NHS [Walley2006] is that PFM has to be specific to each patient stream, and tailored for care pathways and clinical processes. Models of care [Ben-Tovim2008a, McGrath2008, Ben-Tovim2008b] have been used in New South Wales,

Australia, in the Emergency Department: “See & Treat, FastTrack, 3-2-1 Process, Short Stay Units, Integrated care” are structuring and streaming patient flows such that Care Pathways can be more easily applied

The main PFM functions are [Litvak2010, Brent2003]:

- Flow Management (patient, work)
- Scheduling (staff, OR, patient)
- Demand/Capacity Management
- Bed Utilization Management
- Mobile access to data

One of the major tools in PFM is Variability Methodology [PMVHD2006, Litvak2010, IHI2003]. The main cause of bottlenecks in patient flows is variability in the demand and in the services. The main objective of PFM is to eliminate artificial variability, introduced by sub-optimal processes, and mitigate natural variability (i.e patient arrivals at ED) as much as possible. Several hospitals across the world have achieved outstanding successes in redesigning their patient flows [Ham2003, AHA2010, CHF2011, NHS2006].

2.1.5 Clinical Operations Support Systems (COSS)

A Clinical Operations Support System (COSS) is a Clinical Information System for Physicians, Nurses, and other care providers that supports them in daily clinical operations management. A COSS is not an Electronic Health Record (EHR) system but interfaces with such systems as needed. A COSS implements the following types of functions:

- Care Process Management
 - Task Management
 - Decision Support
 - Notifications, Communications, Collaboration
- Demand Capacity Management
 - Scheduling and Booking

- Staffing
- Staffing to Census
- OR Utilization
- Bed Occupancy
- Off-Servicing
- Use of Flex/Unfunded Beds
- Isolation requirements
- Telemetry needs; Ventilator needs
- Demand forecasts
- Discharge plans
- Performance Management
 - Performance Measurement
 - Performance Analysis: Key Performance Indicators, Outcomes/Process Indicators
 - Performance Reporting
 - Operational Business Intelligence (Real-Time Performance Management)
- Quality of Care, Safety & Risk Management
 - Adverse Event Management
 - Patient Safety planning & management; Patient Safety reporting
 - High-Alert Medication management
 - Medical Device Management
 - Infection Control
 - Risk Management: falls, pressure ulcers, skin & wound care, suicide prevention, VTE prophylaxis, home safety assessment

Examples of COSS modules are:

- Patient Flow Management System
- Bed Management; Capacity Management
- Adverse Event Management System
- Infection Control System
- Operational Business Intelligence

- Patient Relationship Management
- Care Process Management
- Clinical Risk Management System
- Patient Safety Planning & Management

There are stand-alone applications on the market providing these functions. However, they are not interoperable, they are not integrated, they are not sharing the same information model, they are not patient-centric, and they are not process-driven. COSS are next-generation applications.

Being part of the COSS suite, Decision Support Systems (DSS) have been extensively used in Healthcare [Oliveira2002, Berner2009] for order entry, medication validation, and support to diagnosis.

2.2 Value-based Hospitals and Service Lines

2.2.1 Institute of Medicine Recommendations

Value-based hospital is a new approach to managing care that is emerging in response to challenges faced in the health care system. In September 2012, the Institute of Medicine published a report [IOM2012] about “Best Care at Lower Cost: The Path to Continuously Learning Healthcare in America”. The best possible care is indeed technologically possible in industrialized countries, at a lower cost than what we are currently paying for a less effective system; and there is urgency to do so. The onus is on the Healthcare IT industry to provide better support to Physicians and Nurses when they carry out their day-to-day tasks. A hospital Nurse is spending only 30% of her time on Patient Care; the rest is spent on administrative, collaborative, and data entry tasks. A Physician working 8 hours a day on delivering care would need to work 21 hours a day if they were to strictly follow medical guidelines. Among the recommendations made by the IOM Committee, it is strongly advised that hospitals adopt Operations Management techniques, which have

been used in other industries like automobile, transport, telecommunications, banking, etc.

In particular, recommendations 1,3,7, and 9 in the figure below are not yet met by the healthcare industry. These delineate the domain of Clinical Operations Management for supporting value-based hospitals

Foundational Elements

➡ **Recommendation 1: *The digital infrastructure.*** Improve the capacity to capture clinical, care delivery process, and financial data for better care, system improvement, and the generation of new knowledge.

Recommendation 2: *The data utility.* Streamline and revise research regulations to improve care, promote the capture of clinical data, and generate knowledge.

Care Improvement Targets

➡ **Recommendation 3: *Clinical decision support.*** Accelerate integration of the best clinical knowledge into care decisions.

Recommendation 4: *Patient-centered care.* Involve patients and families in decisions regarding health and health care, tailored to fit their preferences.

Recommendation 5: *Community links.* Promote community-clinical partnerships and services aimed at managing and improving health at the community level.

Recommendation 6: *Care continuity.* Improve coordination and communication within and across organizations.

➡ **Recommendation 7: *Optimized operations.*** Continuously improve health care operations to reduce waste, streamline care delivery, and focus on activities that improve patient health.

Supportive Policy Environment

Recommendation 8: *Financial incentives.* Structure payment to reward continuous learning and improvement in the provision of best care at lower cost.

➡ **Recommendation 9: *Performance transparency.*** Increase transparency on health care system performance.

Recommendation 10: *Broad leadership.* Expand commitment to the goals of a continuously learning health care system.

Figure 2-3 Recommendations Relevant to COM for Value-based Hospitals

[IOM2012]

2.2.2 Value-Based Hospitals

Currently, hospitals are organized by medical units and by specialties; these tend to operate in silos, without much communication between them. The transitions of care are not optimal for the patients, thus negatively impacting the patient outcomes. This is

shown as the “vertical” organization in Figure 2-4 Value-based Hospital [BCG2014] below, from the Boston Consulting Group [BCG2014]. Another emerging organization, called value-based, focuses on a group of patients with similar condition, a cohort, and provides them with end-to-end care across units and specialties, throughout the hospital. This “horizontal” organization is patient-centric, instead of provider-centric. It provides better patient outcomes and is cheaper [BCG2014].

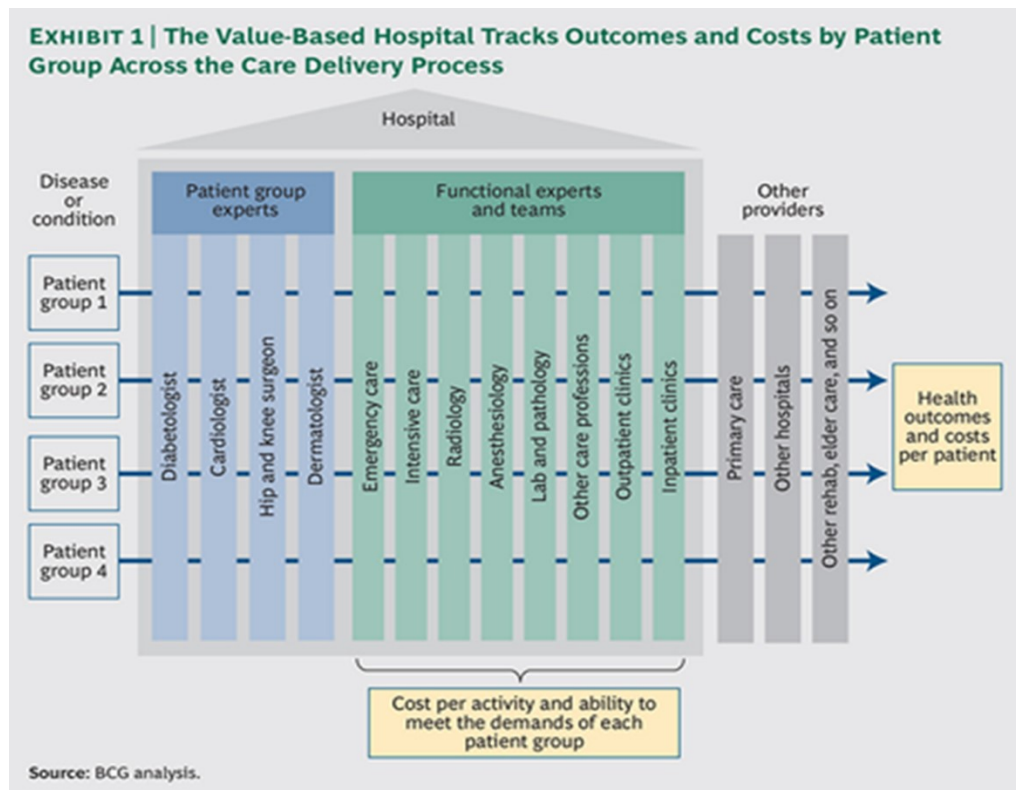


Figure 2-4 Value-based Hospital [BCG2014]

An example of such value-based organization is the Service Line concept, widely deployed by the NHS in the UK. See section 2.2.3.

Across the world, the trend towards value-based care versus the current Fee-for-Service model is transforming the Healthcare system. Instead of being reimbursed for the volume of procedures/consultations/orders they perform, Healthcare Providers will be reimbursed based on the quality/value in health care they deliver. And the reimbursement will be for

an end-to-end service to the patient, meaning that Primary Care, Hospitals, Community Care Providers will have to work together in order to minimize their end-to-end costs and maximize the end-to-end care value delivered to the patient. In the US, such value-based care is driven by the Affordable Care Act and emergence of Accountable Care Organizations. In Ontario, it is the Health System Funding Reform and the Quality-Based Procedures. In Europe, similar initiatives have been put in place in most countries.

The impact on hospitals is huge. They will have to track their end-to-end costs and delivered value at a granular level that has never been done so far.

An example from Ontario will help understand the challenge faced by hospitals. Currently, each Healthcare Provider involved in a Clinical Service (for instance Orthopedic Surgery) would get reimbursed on a Fee-For-Service model: The Family Physicians having referred the patient for surgery, the Surgeon performing the procedure, the Anesthetist performing the induction, the Hospital where the procedure takes place, the Rehabilitation center for post-surgery care, etc, will get reimbursed separately for their service, whether it was done optimally at the highest possible quality level and lowest possible cost... or not. With the advent of Quality-Based Procedures, the Healthcare Payer will reimburse a fixed sum for the end-to-end service delivered to the patient. This fixed sum is the average of the cost for such procedures performed in all hospitals across Ontario. This means that for half of the hospitals, their actual cost will be lower than the fixed reimbursement sum, and therefore they will make a positive margin, and for the other half of hospitals, they will actually make a negative margin. In parallel, the quality of the care delivered is monitored, and any re-admission within 30 days of the patient will not be reimbursed.

As can be seen, this trend towards value-based care will trigger a major shift in the Healthcare industry. Hospitals will have to control their end-to-end costs and end-to-end Quality-of-Care. Their current Information Systems are based on the current Fee-For-Service model, give visibility on Units instead of end-to-end Clinical Service, are not geared towards end-to-end capacity management, do not provide end-to-end performance

reporting, have no visibility on end-to-end care processes, and do not provide real-time decision support at the point-of-care.

2.2.3 Service Lines

A service line is organized around patient groups (cohorts), or groups of diseases, and is based on end-to-end care pathways like Hip & Knee Replacement, or Hip Fracture for instance. The service line covers the patient's journey through the entire hospital. For the Hip Fracture for instance, the journey includes the Emergency Department, the Diagnostic Imaging, the Lab tests, the surgical procedure in the Operating Room, the stay in the Surgery unit, and the Rehabilitation, then discharge from hospital.

Taking the example of Cleveland Clinic [CC-SLM], the Department of Orthopaedic Surgery and the Department of Rheumatic and Immunologic Diseases have created the Orthopaedic and Rheumatologic Institute, a Service Line providing the following list of clinical services:

- Hand, Wrist, Elbow & Shoulder Surgery
- Foot & Ankle Surgery
- Hip & Knee Surgery
- Trauma Surgery
- Tumor Surgery
- Spine Surgery
- Pediatric & Adolescent Orthopaedic Surgery
- Orthotics & Prosthetics
- Musculoskeletal Physical Medicine & Rehabilitation
- Sport Health
- Concussion
- Rheumatic and Immunological Diseases
- Arthritis

The Institute is providing end-to-end bone, muscle, and joint care.

The NHS in the UK has undertaken a major push towards the service line organization. The Independent Regulator of NHS Foundation Trusts, Monitor, has published a series of guidebooks [NHS-SLM2009] on Service Line Management. There are 4 key enablers of Service Line Management:

- A matrix organization, with clear leadership roles and well-defined decision rights.
- A strategic and annual planning process, with a long-term competitive strategy backed by annual action plans to deliver the strategy, and quarterly reporting.
- A Performance Management system, with clear indicators and targets, solid monitoring, and rewards and consequences for performance.
- An Information System capable of delivering relevant and timely information, and patient-level costing.

One sign of a hospital transformation towards value-based hospital is an increased number of Service Lines.

2.2.4 Hospital Transformation

COM is critical to transform a hospital, just like Operations Management has been critical to transform other industries like Telecoms.

The American Hospital Association [AHA2014] has identified 10 must-do strategies for hospitals to transform themselves; 4 of these were major priorities:

- “Aligning hospitals, physicians, and other providers across the continuum of care
- Utilizing evidence-based practices to improve quality and patient safety
- Improving efficiency through productivity and financial management
- Developing integrated information systems”

Frameworks for business transformation via innovative operations management have been proposed [HBR2004]; they include, among others:

- Organization Redesign

- Process Redesign
- Information System Redesign

The Joint Commission [TJC2008] has proposed guiding principles for the design of the hospital of the future; they include among others:

- “Apply process improvement tools to improve efficiency and reduce costs
- Redesign business and care processes in tandem with health information technology to ensure benefit accrual
- Use digital technology to support patient-centered hospital care...
- Make adoption of patient-centered care values a priority for improving patient safety and patient and staff satisfaction
- Support the development of health professional knowledge and skills required to care for patients in an increasing complex environment...”

2.3 Enterprise Architecture

2.3.1 TOGAF

The Open Group, a vendor-neutral and technology-neutral consortium whose mission is “to make standards work”, has released TOGAF, a standard for Enterprise Architecture methodology and framework [TOGAF9]. Figure 2-5 Enterprise Architecture definition [TOGAF9] gives their definition of Enterprise Architecture:

What is Enterprise Architecture?



[1] MIT Center for Information Systems Research
[2] SearchCIO.com

Enterprise Architecture is:

- The organizing logic for business processes and IT infrastructure reflecting the integration and standardization requirements of the firm's operating model.[1]
- A conceptual blueprint that defines the structure and operation of an organization. The intent of an enterprise architecture is to determine how an organization can most effectively achieve its current and future objectives. [2]

TOGAF®

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Figure 2-5 Enterprise Architecture definition [TOGAF9]

One of the main reasons for building an Enterprise Architecture is to lead the business transformation of the enterprise. Here, this means the transformation of hospitals towards value-based hospital; the COM domain is where the transformation is taking place.

TOGAF has identified 4 types of architectures, per Figure 2-6 TOGAF Architecture Types [TOGAF9]:

- Business Architecture
- Information System Architecture which includes Application Architecture and Data Architecture
- Technology Architecture

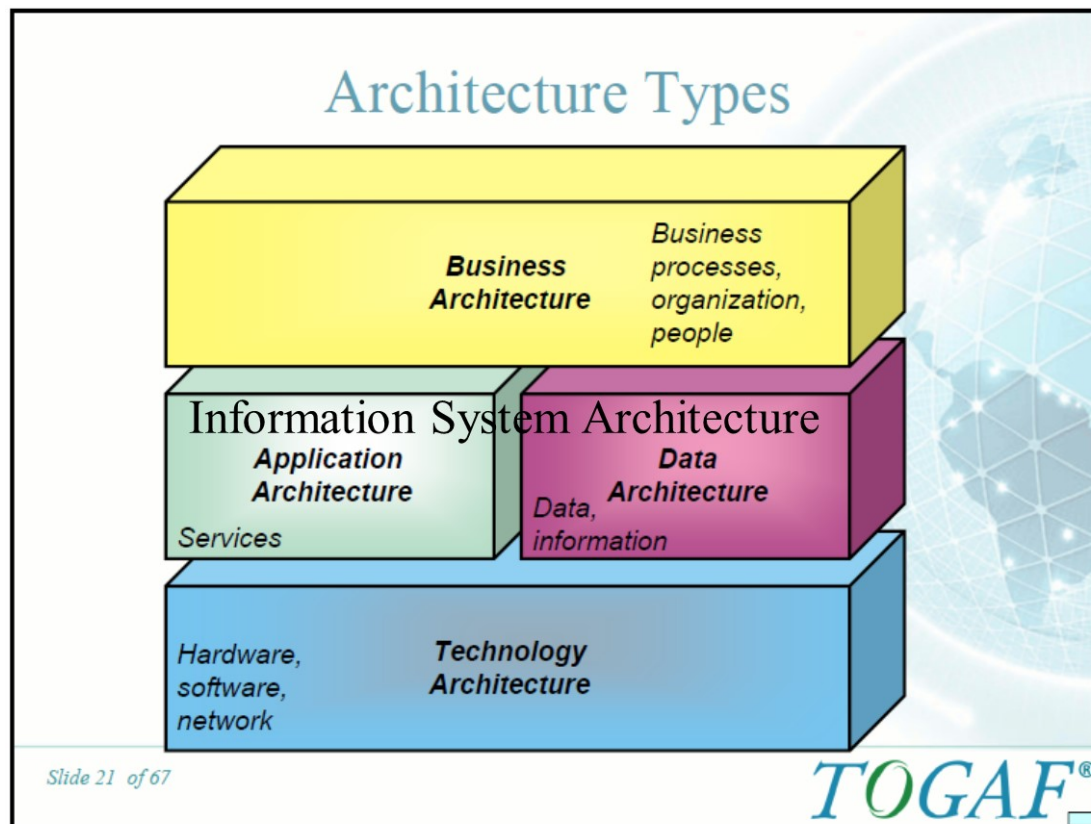


Figure 2-6 TOGAF Architecture Types [TOGAF9]

TOGAF describes an Enterprise Architecture Development Method (ADM), per Figure 2-7 TOGAF Architecture Development Method [TOGAF9]:

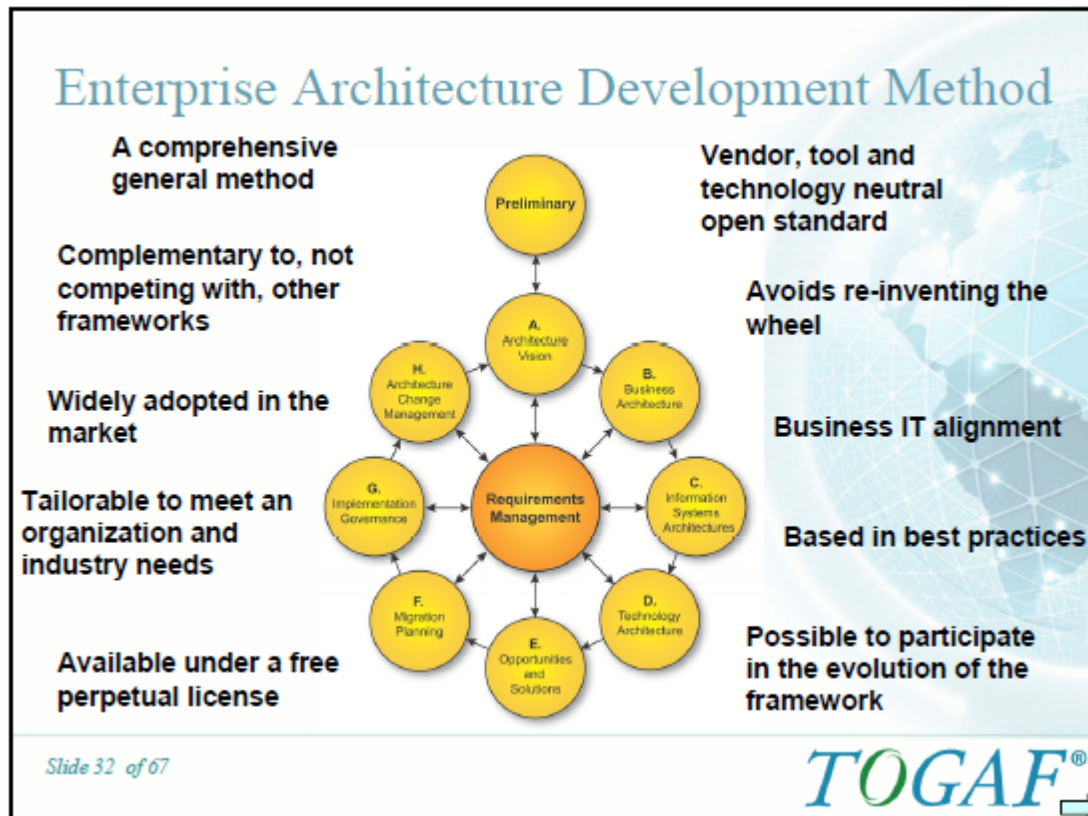


Figure 2-7 TOGAF Architecture Development Method [TOGAF9]

2.3.2 ArchiMate

The Open Group has also released ArchiMate [ARCHIMATE2], a modeling language for Enterprise Architecture which has been aligned with the TOGAF Architecture Development Method, per Figure 2-8 TOGAF ADM and ArchiMate [ARCHIMATE2]:

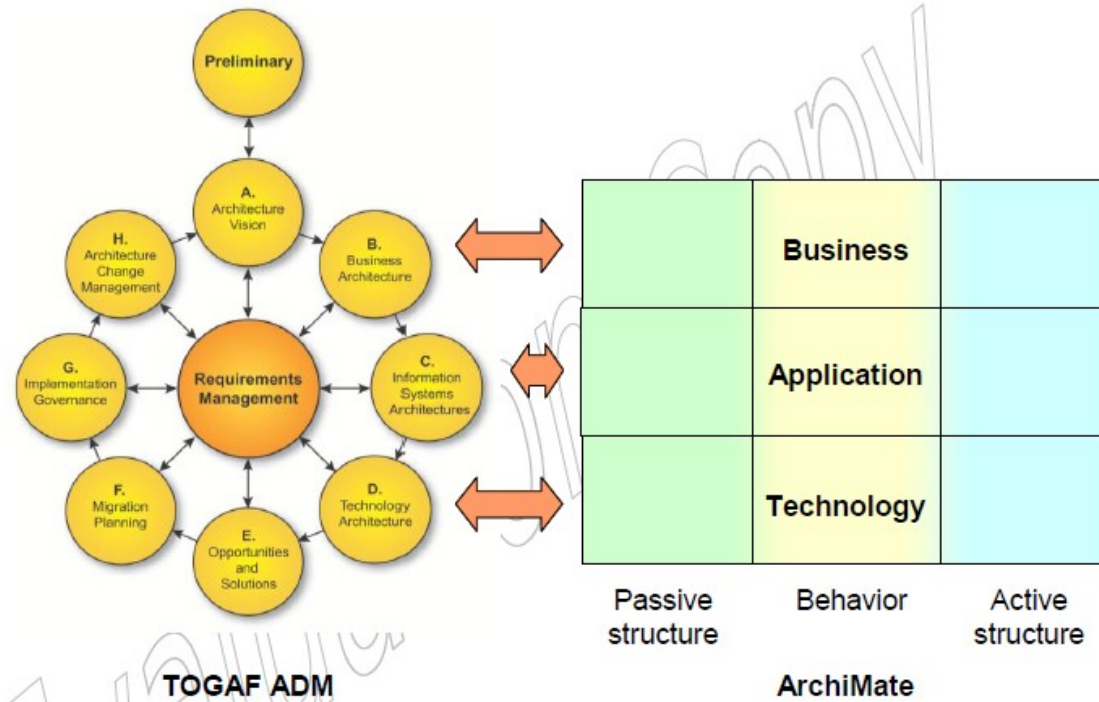


Figure 2-8 TOGAF ADM and ArchiMate [ARCHIMATE2]

2.3.3 Enterprise Architecture in Healthcare

Several Healthcare organizations have developed an Enterprise Architecture to guide their business transformations:

- New South Wales Health [NSW2004]
- Queensland Health [QH2014]
- Cancer Care Ontario [CCO2014]

2.4 Model-Driven Engineering and Model-Driven DSS

2.4.1 Model-Driven Engineering (MDE)

With the increasing complexity of software development, a recent discipline has emerged based on modeling to represent problems to be addressed by the information systems: Model-Driven Engineering (MDE). Models are used as blueprints, as means for documenting and communicating, and now as programs. Models are becoming first-class entities in Software Engineering [Brambilla2012]. The software is produced following a series of transformations on models. Figure 2-9 Overview of MDE methodology [Brambilla 2012] gives an overview of the methodology.

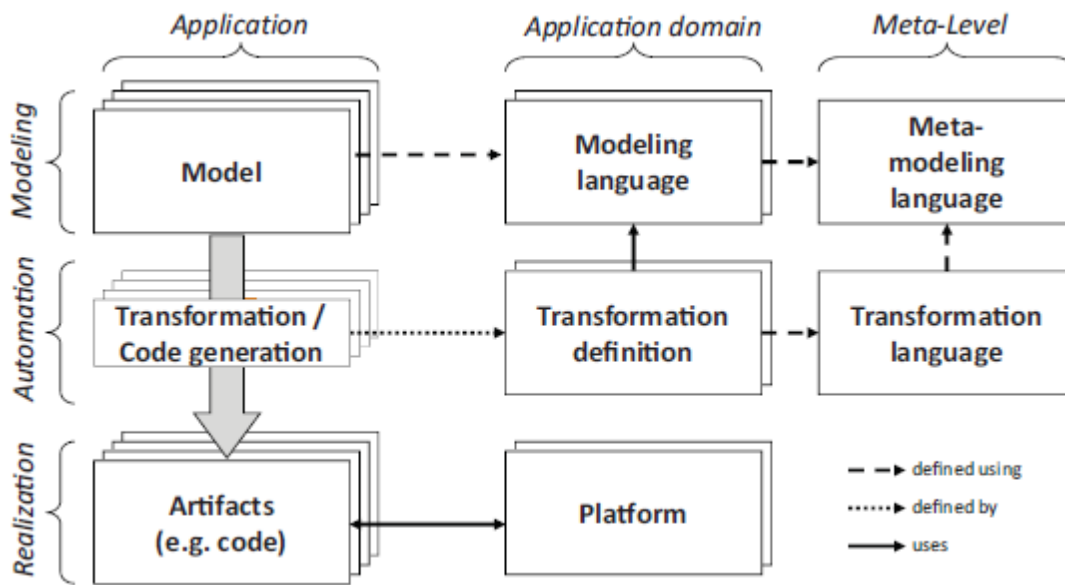


Figure 2-9 Overview of MDE methodology [Brambilla 2012]

The modeling is done with a modeling language conforming to a metamodel, per Figure 2-10 MDE metamodeling stack [Brambilla2012] showing the 4-level metamodeling stack:

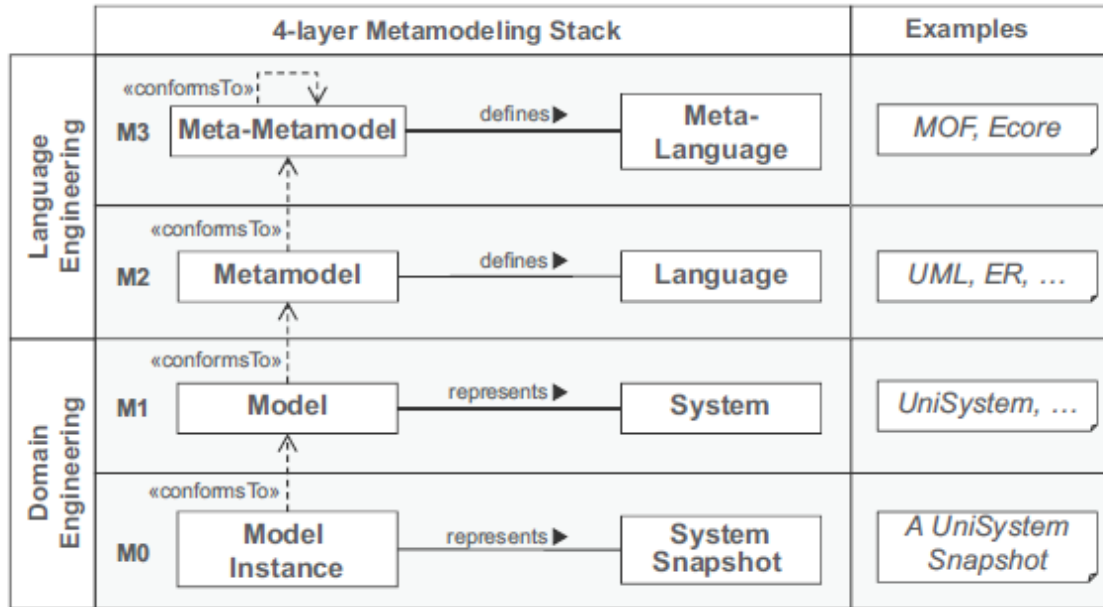


Figure 2-10 MDE metamodeling stack [Brambilla2012]

The most well-known instance of MDE is the Model-Driven Architecture (MDA) standard from the Object Management Group: MDA v2.0 is described in [OMG-MDA2014]. MDA defines 3 levels of abstraction in modeling, as shown in Figure 2-11 MDA levels of abstraction [Brambilla2012] and [OMG-MDA2014]:

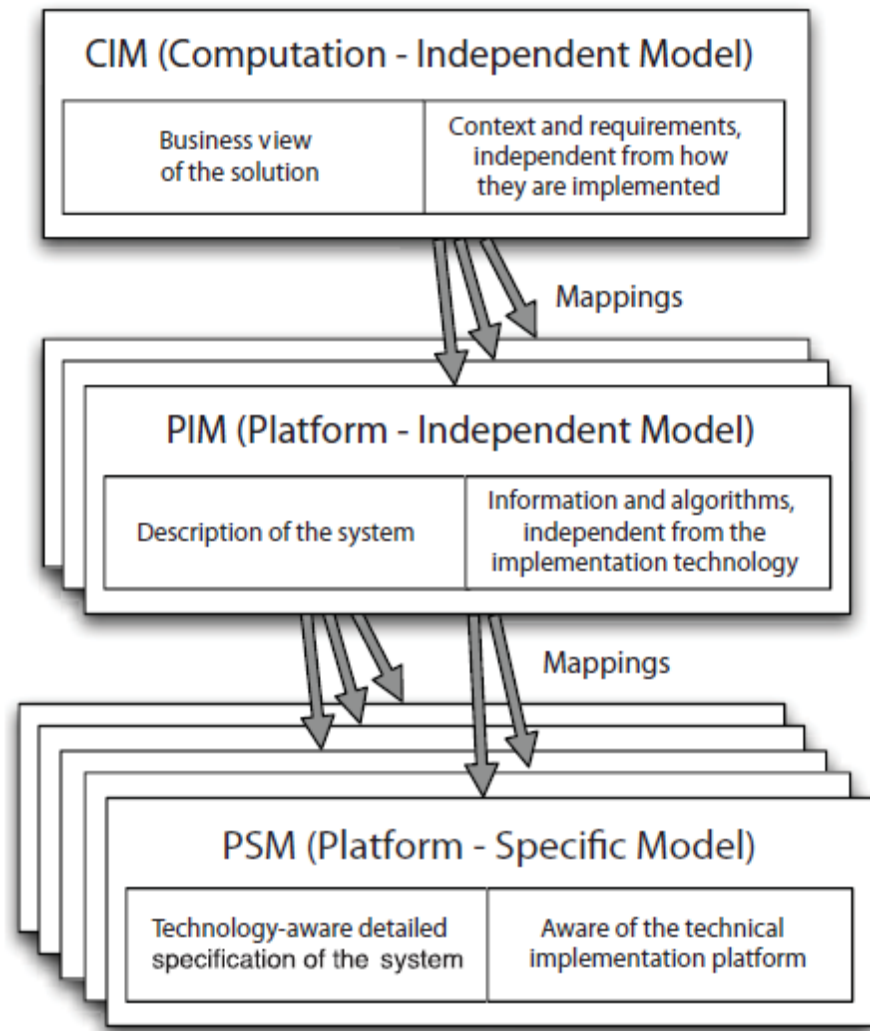


Figure 2-11 MDA levels of abstraction [Brambilla2012] and [OMG-MDA2014]

Several OMG Standards [OMG] are related to MDA:

- UML (Unified Modeling Language) conforming to its metamodel MOF (Meta Object Facility)
- SOAML (SOA Modeling Language) which is a UML Profile
- A series of domain-specific UML Profiles
- BPMN (Business Process Model and Notation)
- DMN (Decision Model and Notation)
- CMMN (Case Management Model and Notation)

- Note: OMG has published white papers [OMG] showing possible ways to link their standards:
 - UML is linked to BPMN/DMN via UML Activities (Behaviour Objects) which can be implemented as BPMN processes and/or DMN decision nodes.
 - BPMN decision tasks can be implemented as DMN decision nodes
 - OMG has standardized interfaces of Clinical Decision Support Services which can be implemented as DMN Rules services, for instance.

2.4.2 TOGAF and MDA

The Open Group and the Object Management Group have worked on building bridges [TOG-OMG] between TOGAF and MDA as shown in Figure 2-12 Synergy between TOGAF ADM and OMG MDA and Figure 2-13 TOGAF and MDA Synergy Points below:

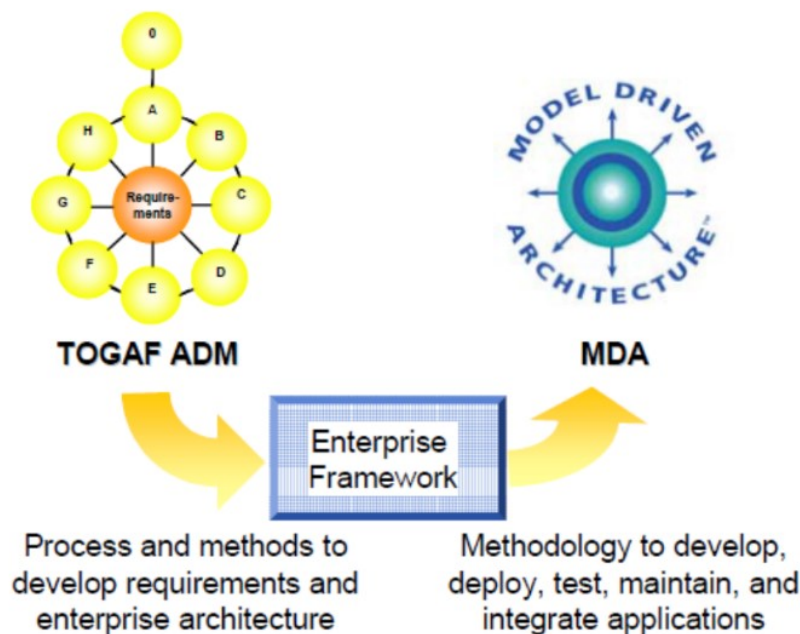


Figure 2-12 Synergy between TOGAF ADM and OMG MDA [TOG-OMG]

	CIM	PIM	PSM	PM	Transformations
ADM Phase A	A	A	NA	NA	NA
ADM Phase B	A	A	NA	NA	NA
ADM Phase C	NA	A	NA	NA	NA
ADM Phase D	NA	NA	A	A	A
ADM Phase E	NA	NA	U	NA	NA
ADM Phase F	NA	NA	NA	NA	NA
ADM Phase G	NA	NA	U	U	U
ADM Phase H	NA	NA	NA	NA	NA

A – Applicable in that TOGAF indicates that models like these be created
NA – Not Applicable only in that these models are not produced at this phase
U – Useful in this phase

Figure 2-13 TOGAF and MDA Synergy Points [TOG-OMG]

2.4.3 Model-Driven DSS and Blackboard Architectural Pattern

Model-Driven Decision Support Systems are a fairly new discipline [Power2005] emerging at the same time as Model-Driven Engineering, but there have been few interactions between them. Model-Driven DSS are based on the premises of inferencing (reasoning) made on the model itself. The models might be object models, process models, event models, functional models, rules models, Multi-Criteria Decision Analysis (MCDA) decision models, Discrete-Event Simulation models, Optimization models, or simply spreadsheets.

Blackboard Systems [Nii1986] can be considered as Model-Driven DSS, even though they were invented earlier. Blackboard systems are well-suited for problems for which no deterministic solution strategy is known, that is very complex problems. Blackboard systems have been used, for instance, in Voice Recognition: Hearsay and Hearsay2 projects [Nii1986]. They have also been used in Operations Management [Sadeh1998] for the integration of Process Planning and Production Scheduling.

In Blackboard systems, several Knowledge Sources assemble their knowledge and pool their inferencing capabilities in order to build a solution to a complex problem which could be partial or approximate. The Knowledge Sources collaborate by sharing a Blackboard structure on which facts are written and seen by all, and each contributing to the creation of new facts leading to a solution, under the coordination of a Control entity. A typical Blackboard Architectural Pattern [Buschmann1996] is shown in Figure 2-14 Blackboard Architectural Pattern [Buschmann1996] below:

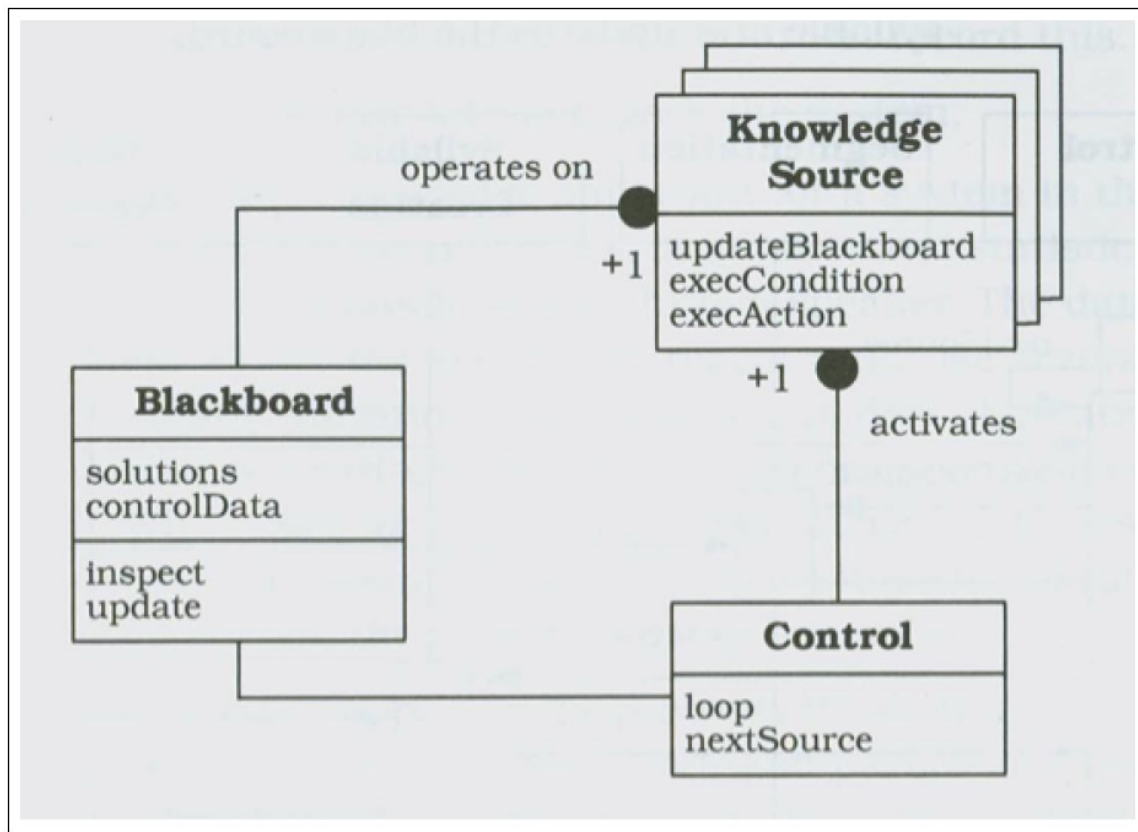


Figure 2-14 Blackboard Architectural Pattern [Buschmann1996]

In the 1990s, Blackboards have suffered from scalability to real world applications. In the case of hospital COM, the domain knowledge is vast but definitely bounded. Also, languages like Java and C# now offer object monitoring capabilities in a multi-threaded environment that did not exist at the time. The hospital COM domain is well suited for Blackboard systems because it is complex, intrinsically model-based, with expert knowledge, of which most can be transferrable from one hospital to another. Blackboard

systems have been very successful in Operations Management in other industries [Sadeh1998]. We are going to use the technology in our COM Platform.

2.4.4 Tools

The Eclipse Modeling Project [EMF] is an Open Source tool suite for Model-Driven Engineering. It includes the following tools, among others:

- The core EMF framework with its metamodel Ecore. Major features are change notification, persistence support, and reflective API.
- The EMF Editor and the EMF code generator
- Papyrus, a UML modeling tool built on top of EMF
- Acceleo: a Model-to-Text Transformation tool built on top to EMF, which can generate Java code

Another open source UML modeling and execution tool compatible with EMF is Modelio, from ModelioSoft [Modelio]. It also supports SOAML and BPMN modeling and execution.

DROOLS is an open source tool suite supporting BPMN with a Process Engine, supporting Rules-based DSS with a Rules Engine, and supporting Complex Event Processing (CEP) with an Event Engine. The suite [DROOLS] includes:

- DROOLS Expert: Object-Oriented Rules Engine, executing rules written in DROOLS Rules Language. It is capable of supporting Blackboard systems.
- DROOLS Guvnor: Repository & Authoring WorkBench
- DROOLS Flow: supports BPMN modeling, and Process Engine (jbpm).
- DROOLS Fusion: Event Engine

The DROOLS team has committed to support DMN with its Rules Engine, but this capability is not available yet, as of April 2016 when this thesis work has completed.

Camunda [CAMUNDA] is an open source tool supporting BPMN, CMMN, and DMN modeling and execution; it is not yet compatible with DROOLS Expert.

Commercial DMN modeling and execution tools compatible with Drools Expert (DecisionsFirst Modeler, Sygnavio) are currently available on the market.

2.5 Enabling Technologies

The approaches presented so far are core to our COM Platform. Here is a set of related technologies needed to build Clinical Operations Support Systems.

2.5.1 Analytics and Business Intelligence

Until recently, Analytics and Business Intelligence have been used in Healthcare primarily for Historical Performance Reporting to the Payer (Ministry of Health in Ontario [HQO2011], or Australian Government [AIHW2008]).

A trend is emerging where hospitals are using BI also for measuring historical operational performance [Hatch2008, Welch2010], with dashboards. This data is then used to gain further insight for decision-making.

We are expanding upon this approach in our research to create real-time analytics which could enable real-time decision making.

2.5.2 Business Process Management

BPM has been successfully used for process improvement initiatives in other industries for many years [Hess2009], but it is still a relatively new concept in Healthcare [Han2006, Reichert2011, Lenz2007].

Some key challenges to address in Healthcare, because of the very high human interaction, are Process flexibility [Mans2008a, VanderAalst2008, Schonenberg2007] and Process Exception Management [Adams2007, Russell2006a]. Another challenge is applying Model-Driven Engineering to care processes [Rabbi2012].

A new sub-discipline in BPM is emerging, which is Process Mining [Mans2008b, Mans2012]. Its application in Healthcare would enable the automatic mining of current processes, the assessment of how much they actually differ from what they should be, and then drive the process improvement initiatives.

[Weber2008] has identified the requirements for flexibility and proposed Change Patterns for enhancing flexibility in Process-Aware Information Systems (PAIS), as described in the Figure 2-15 Adaptive Process-Aware Information System [Weber2008] below. We are using this approach in our Decision Support service for BPM.

Adaptive PAIS: Need for Flexibility Support

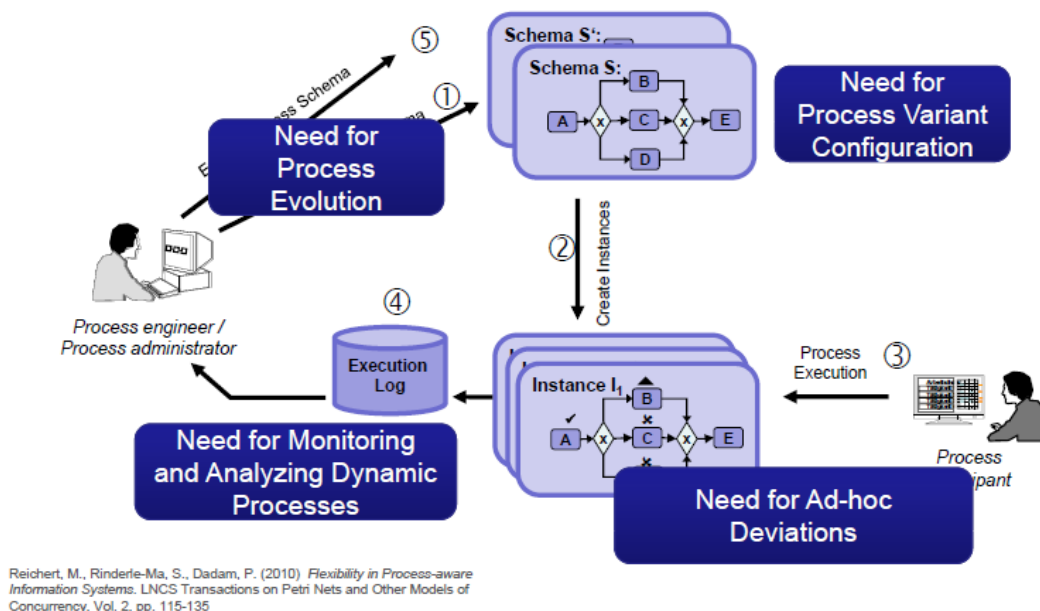


Figure 2-15 Adaptive Process-Aware Information System [Weber2008]

2.5.3 Real-Time Location System (RTLS)

RFID tags and badges, using WiFi and infrared/ultrasound technology, can be used to track people inside a building, with an accuracy of 2-3m (WiFi) and 0.5m (IR). The person's (or asset) location is displayed on a map of the floor. The RTLS design requires a survey of the wireless signals on the floor, followed by calibration. This takes a few hours per floor typically [Ekahau2012].

RTLS is starting to be used in hospitals [Marjama2006, Chowdhury2007, Fuhrer2006] to track patients, staff, and medical equipment.

In Ontario, 2 hospitals (Humber River, Rouge Valley) have deployed RTLS in their Emergency Departments.

We intend to use RTLS to automatically measure some wait times and service times, without increasing the burden on Clinicians.

2.5.4 Complex Event Processing (CEP)

CEP is a Rules engine enabling the correlation of all incoming events in time and space, for the purpose of real-time reactivity to changes in the context [Vitria2010]. Low-level events (i.e patient in ED assessment room; step of care: blood test results available) are correlated into high-level complex events, using the rules and policies (i.e Wait Time for Physician Re-Assessment has started).

Recently, the CEP technology is also being used in hospitals jointly with RTLS [Yao2011] for the purpose of tracking people and assets.

In our research, the CEP provides support for real-time analytics and decision-making.

2.5.5 Mobility and Mobile Devices

Smartphones and Tablets bring clinical/operational data and knowledge at the point-of-care, when needed, as part of the workflow [Chuang2012].

This trend is amplified by the “Bring Your Own Device” model that Enterprises are testing. Hospitals are also testing the BYOD model, first for the Physicians, and then extended to the rest of the staff.

This adoption of Mobile Devices in the hospital creates opportunities for some applications which may be deployed first on Mobile Devices and then on desktop computers. Computerized Physician Order Entry is one such example.

2.5.6 SOAML Modeling

SOAML is a UML Profile for modeling SOA services. It is at the heart of Model-Driven Engineering. The OMG SOAML v1.0.1 specification is available at the OMG web site [OMG].

The SOAML methodology is the following:

- Definition of a Services Architecture
- Identification of Participants
- Definition of Service Interfaces
- Design of Components
- Choreography of services
- Orchestration of Components

2.5.7 Discrete Event Simulation

Discrete Event Simulation (DES) has been extensively used in Healthcare for capacity planning [Pirolo2009, Cardoen2007], for scheduling operations [Thorwarth2009,

Komashie2008], for flow modeling [Pearce2010], and for policy assessment [Giachetti2005].

Recently, DES has been used for “short-term simulation” or “Fast-Forward simulation” as we call it [Reijers1999, Rozinat2009, Bahrani2013]. This is to evaluate “what-if” scenarios in order to support decision-making by analyzing the possible impact of a simulated decision.

ARENA is a widely used tool for Discrete Event Simulation [ARENA].

2.5.8 Optimization

Linear Programming techniques, and more generally, optimization techniques have been extensively used for Master Surgery Scheduling [Carter2001, Beaulieu2000, VanEssen2012], and for Nurse Rostering and Staffing [Burke2004, Kortbeek2012, Clark2011].

CPLEX Optimizer is a widely used tool for Linear Programming and Optimization problems [CPLEX].

2.5.9 Multi-Criteria Decision Analysis (MCDA)

Decision Models [Pourshahid2011] and Multi-Criteria Decision Analysis [Mohamadali2009, Dolan2010] have been embedded in Model-Driven Decision Support Systems. [Liberatore2007] presents a literature review of the applications of MCDA Analytic Hierarchy Process (AHP) to problems in medical and healthcare decision-making.

2.6 Related Work

This section describes projects and products against which we are going to compare this research work (in section 6.3). They are not the only projects in this domain, by far, but they each are representative of a critical aspect of the domain and/or approach.

2.6.1 Current Practice

Current Practice in hospital information system strategy is to buy an Electronic Medical Record System and Applications, and deploy them over time following the HiMMS EMR Adoption Model [HiMMS-EMRAM]. These applications are either point products from different vendors (best-of-breed procurement strategy) or integrated applications from the EMR vendors (application suite procurement strategy).

Typical Applications are:

- Patient Flow Management
- Bed Management
- ED information system
- OR information system
- LAB information system
- Diagnostic Imaging systems

These applications usually work in silo, even though the integration could be done via HL7 messaging.

The main EMR Vendors are Meditech, McKesson, Cerner, Epic, etc. They also market Application suites which are well integrated with their EMR, but do not interoperate with others.

COM Applications are seen as an emerging market segment, and the main Vendors in this segment for now are TeleTracking [TELETRACKING] and Medworxx [MEDWORXX].

- TeleTracking is covering the hospital Operations domain with products in Patient Flow Management, Bed Management, Resource Utilization, Asset Tracking, QoC Management, and Labor Productivity
- Medworxx is focused on Patient Flow Management, Bed Management, Performance Management

Current Practice COM applications will be further analysed in sections 3.2.1 and 6.3.1.

2.6.2 CHOIR - Center for Healthcare Operations Improvement & Research

CHOIR is a University of Twente center focused on Operations Management in hospitals [CHOIR]. Their research focusses on Operations Management for:

- Ambulatory Care,
- Surgical Care,
- Inpatient Care,
- Emergency Care,
- Residential Care

They cover the following disciplines:

- Operations Research
- Logistics and Operations Management
- Purchasing Management
- Business analytics, information technology and management
- Quality & Safety Management

CHOIR has a very innovative approach in combining academic research and industrial consulting. Their PhD students work part-time in hospitals.

A research team [Hans2011] has proposed the following Framework for Health Care Planning & Control in hospitals, based on what was done in the Manufacturing industry.

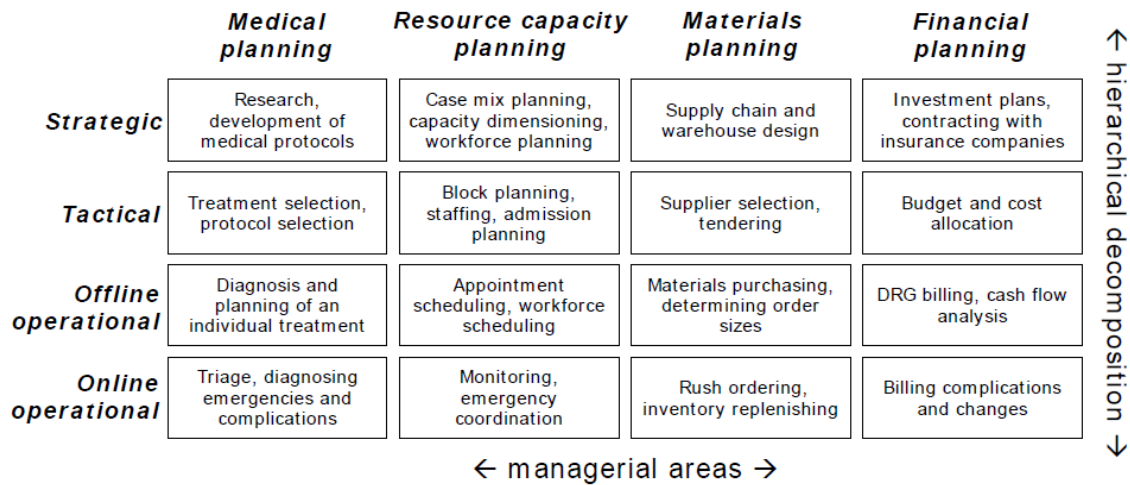


Figure 2-16 Framework for Hospital Care Planning and Control [Hans2011]

Based on this Framework, a taxonomy for resource capacity planning and control decisions in Healthcare has been built [Hulshof2012]. The taxonomy applies the Framework to Ambulatory Care, Emergency Care, Surgical Care, Inpatient Care, Home Care, and Residential care.

This Framework will be analysed in sections 3.2.2 and 6.3.2.

Our approach with Action Research (section 1.4) is very much aligned with theirs; we have found many benefits for both sides in the collaboration between academia and hospitals.

We also share their analysis that Operations Management is a critical domain for hospitals, which has been under-used, whereas it has been proven to be highly beneficial to other industries like Manufacturing, Automobile, Telecommunications, Energy, etc.

One difference with CHOIR is we have a higher focus on information systems and Computer Science, because we believe they can play a critical role in facilitating the deployment of Operations Management in hospitals.

Another difference is their research is structured along the lines of current hospital organization (Vertical): by unit and types of care (ambulatory, inpatient, surgical, emergency, residential). Our research is focused on the transformation of hospitals towards value-based hospitals, with an organization (Horizontal, or more likely: Matrix) centered on service lines that provide end-to-end care to patient cohorts during their journey through the hospital. This difference does have a big impact on the information systems.

2.6.3 MPOWER

The objective of this European Union research project is to use a Model-Driven Engineering approach in order to create a middleware platform that enables rapid development of homecare services and systems for the cognitive disabled and elderly [MPOWER2008].

Their system reference architecture [MPOWERa, b] is shown below:

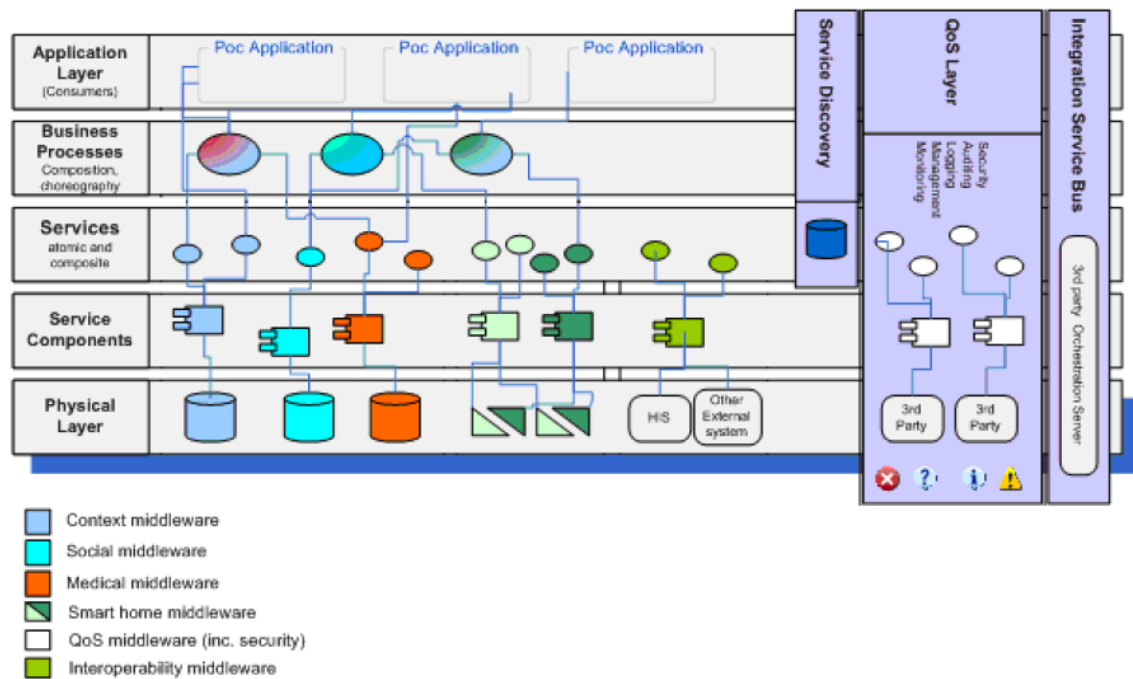


Figure 2-17 MPOWER Reference Architecture [MPOWERa, b]

The MPOWER Homecare UML Profile and SOA UML Profile [MPOWERc] are shown respectively in Figure 2-18 MPOWER Homecare UML Profile [MPOWERc] and Figure 2-19 MPOWER SOA UML Profile [MPOWERc] below:

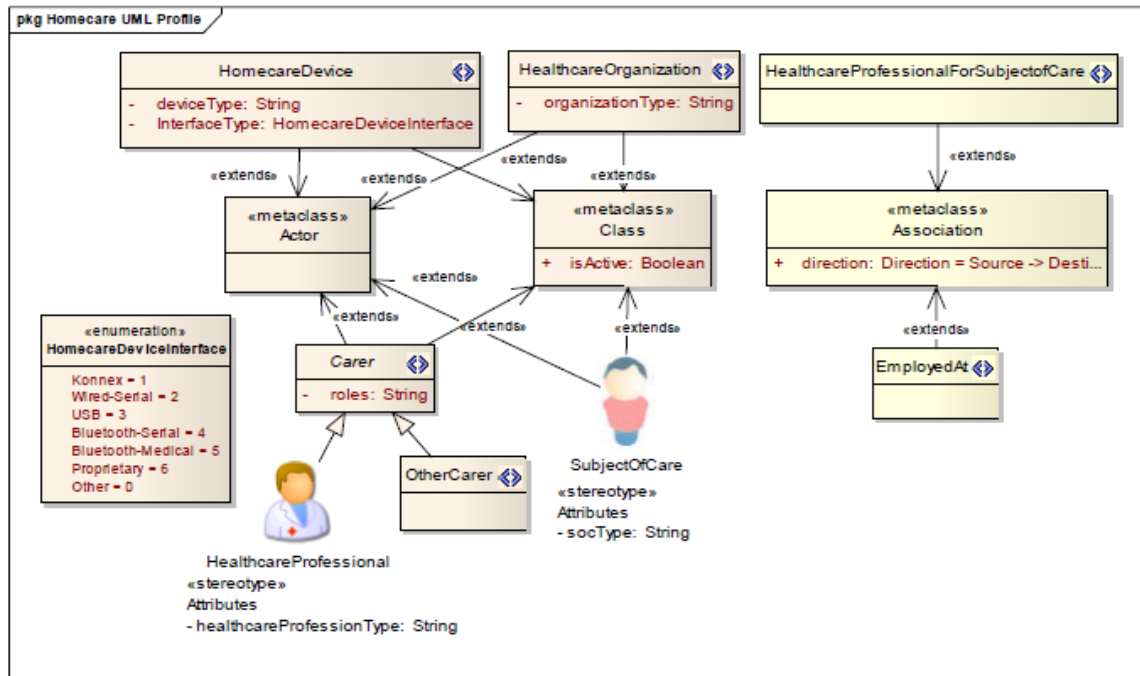


Figure 2-18 MPOWER Homecare UML Profile [MPOWERc]

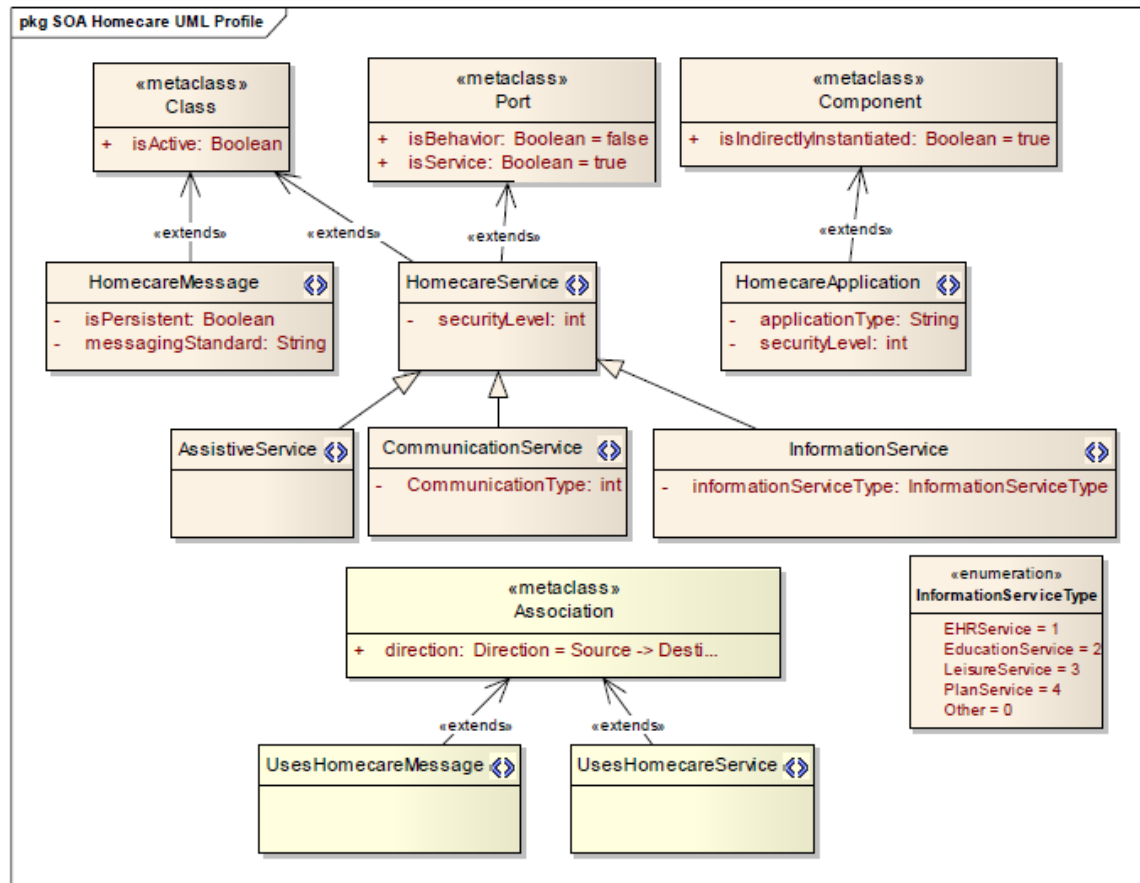


Figure 2-19 MPOWER SOA UML Profile [MPOWERc]

The MPOWER Tool Chain [MPOWERa, d] is shown below:

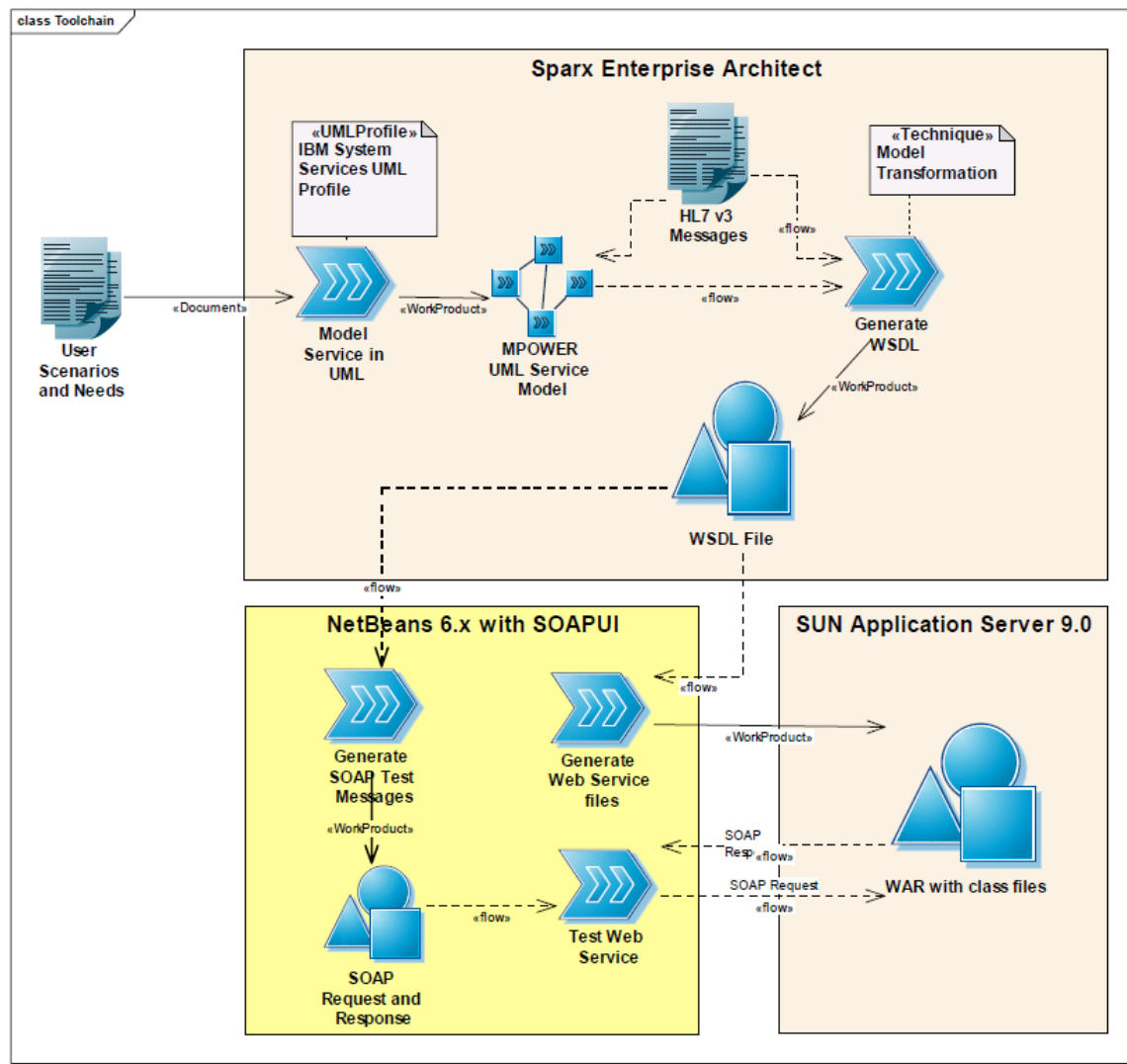


Figure 2-20 MPOWER Tool Chain [MPOWERa, d]

The MPOWER platform will be analysed in sections 3.2.3 and 6.3.3.

Their approach with a Reference Architecture, UML profiles, and Tool Chain is similar to ours, and we have added the figures above for a direct comparison between the 2 platforms.

We share with them the focus on advanced information systems for hospitals, using Model-Driven Engineering. One difference is they are working primarily on the IS

Architecture and the Technology architecture, in the TOGAF Enterprise Architecture, whereas our focus is primarily on the Business architecture. Another difference is their platform is targeting home care applications whereas ours is targeting hospital applications.

There are several other related projects in Healthcare. Of note, [Marmor2009] describes a real-time Decision Support System based on simulation, for Emergency Departments. They have developed a real-time discrete event simulator of operations in ED, and then used it in a Fast-Forward mode in order to predict future bottlenecks in flows. Another team in the same organization [Zeltyn2011a, Zeltyn2011b] has evolved the simulator for real-time operational prediction of staffing requirements, and then planning.

2.6.4 DESSCOM

DESSCOM is an Object-Oriented Decision Support System for Supply Chains, based on object-oriented models and a Model-Driven Engineering approach [Biswas2002].

It is composed of:

- DESSCOM-MODEL, a modeling infrastructure for supply chain elements and dynamic interactions between them.
- DESSCOM-WORKBENCH, a workbench which can potentially include algorithms and simulations for supply chain decision-making.

The architecture of DESSCOM is shown in Figure 2-21 DESSCOM Architecture [Biswas2002]:

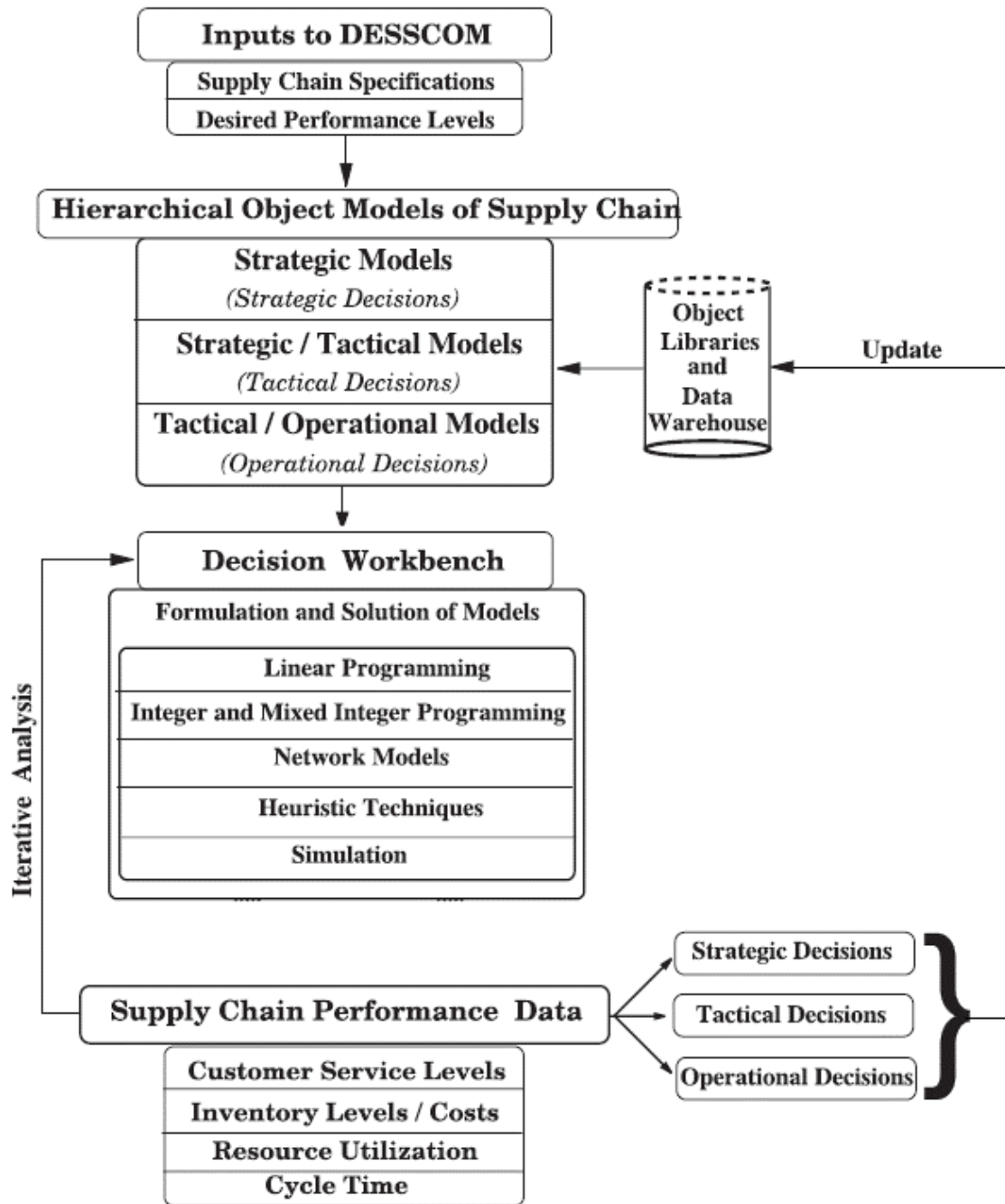


Figure 2-21 DESSCOM Architecture [Biswas2002]

An example of an object model for a Liquid Petroleum Gas (LPG) supply chain is shown in Figure 2-22 DESSCOM Object Model of the LPG Supply Chain [Biswas2002]:

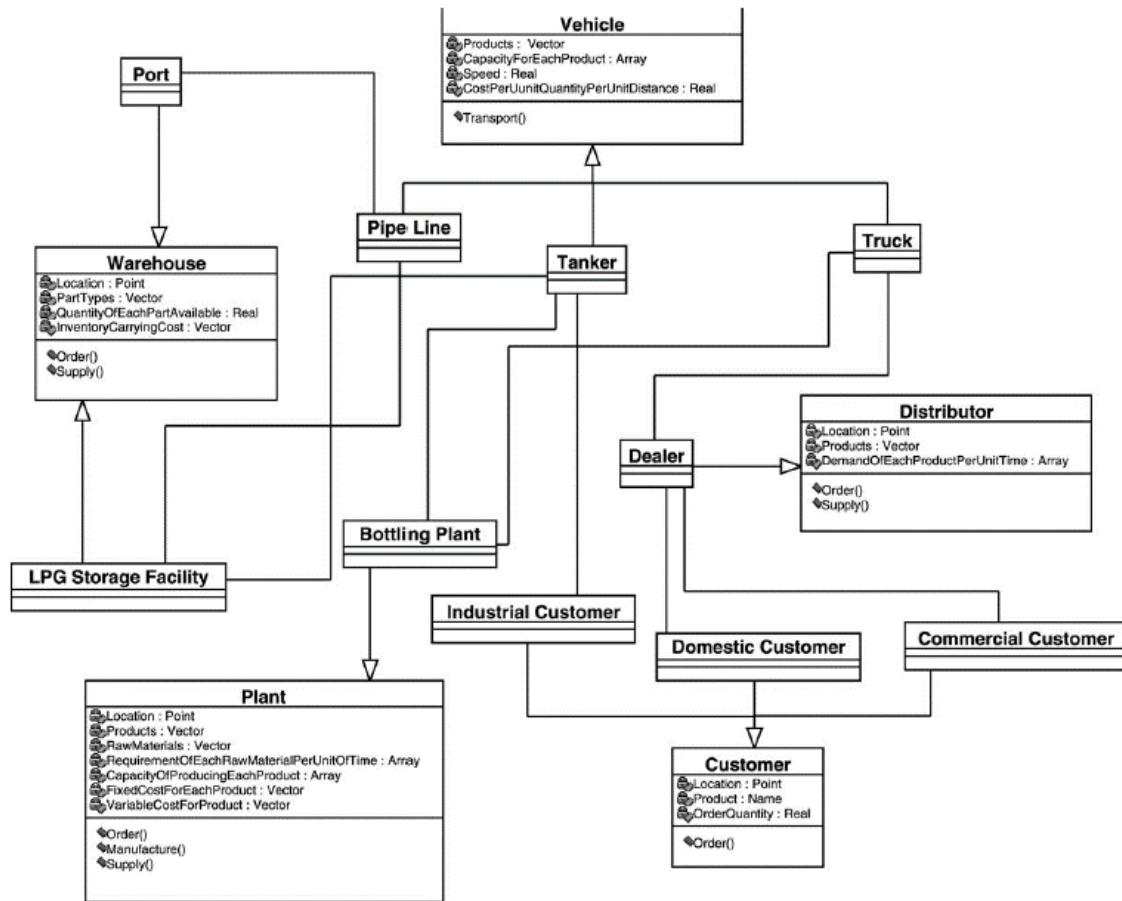


Figure 2-22 DESSCOM Object Model of the LPG Supply Chain [Biswas2002]

The DESSCOM information system will be analysed in sections 3.2.4 and 6.3.4.

Our respective research domains are obviously different, but our research objectives and approaches are very similar. We are both using Model-Driven Engineering and are building models in order to deliver advanced information systems for Operations Management. We are both primarily focusing on the Business architecture of the TOGAF Enterprise Architecture. One major difference is our COM Platform is focusing more on supporting operational decisions in real-time.

3 Problem Definition, Gap Analysis, and Validation Criteria

3.1 Problem Definition

According to the Healthcare Information Management Systems Society (HiMSS) [HiMSS-EMRAM], hospitals across the world are well on their way in the EMR adoption. However, as the American Medical Informatics Association (AMIA) EMR 2020 Task Force [AMIA2020] reports, results are not up to expectations. One of the reasons is the EMR lack of usability for Clinicians; another is that the EMR is not patient-centered enough. The problem is compounded for the COM domain in hospitals. Clinicians use medical information systems; Administration use management information systems. A COM information system is normally used by both sides; however, the domain is not very well understood by either side. We end up having information systems focused on units and medical specialties, per Figure 3-1 below, instead of being patient-centric; they are also working in silos, with limited integration:

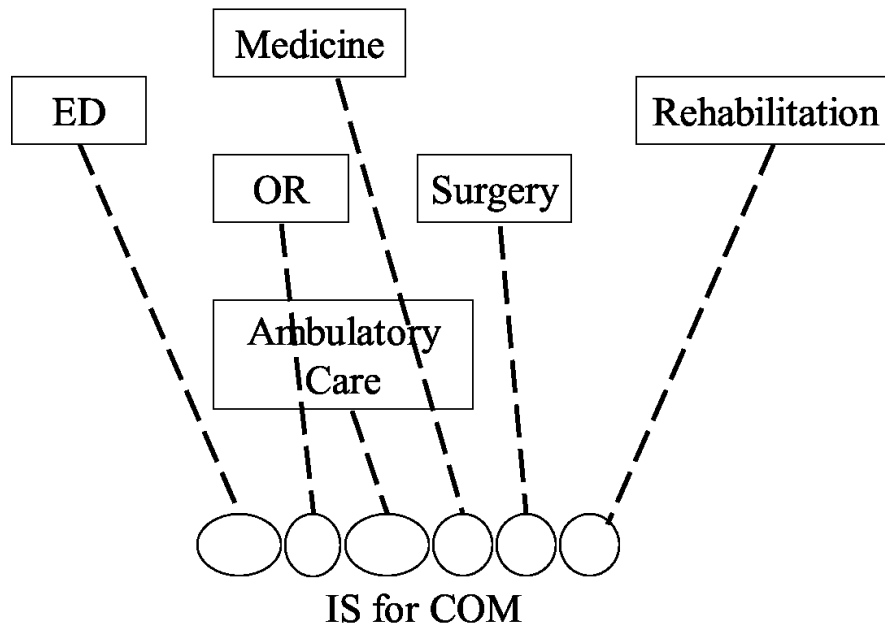


Figure 3-1 Current Unit-based Focus of Hospital IS

This translates into COM information systems that are not integrated, do not cover the end-to-end patient journey through the hospital, and cannot manage the patient flows in real-time. They do not meet user expectations [AMIA2020]. One of the root causes of this is the absence of structured domain models. Operations Management has been understood in other industries for at least 50 years, and yet the discipline is only recently finding its way into Healthcare [IOM2012]. There are plenty of domain models in other industries, but not for entire hospitals, as far as we know. Most of the modeling has been focused on hospital units [IOM2012], not entire hospitals. Furthermore, with the lack of domain models, the Model-Based Engineering approach to the development of information systems, used successfully in the transformation of many other industries, becomes very challenging [OMG-MDA2014]. Another root cause, and compounding factor, is the low usage of enterprise architectures to drive the hospital transformation, unlike what other industries do [IOM2012]. Without an enterprise architecture, the transformation usually happens in an ad hoc way, designed unit by unit instead of being designed as holistic; the implementation is usually not systematic. The experience from other industries shows that this piecemeal approach tends to offload problems elsewhere in the hospital instead of resolving them.

By contrast, Figure 3-2 Patient-centered Focus of Hospital IS in Value-Based Hospitals below shows what the focus of the information systems should be for value-based hospitals: patient cohorts and service lines covering the end-to-end patient journeys through the entire hospital. This is done with better integrated information systems.

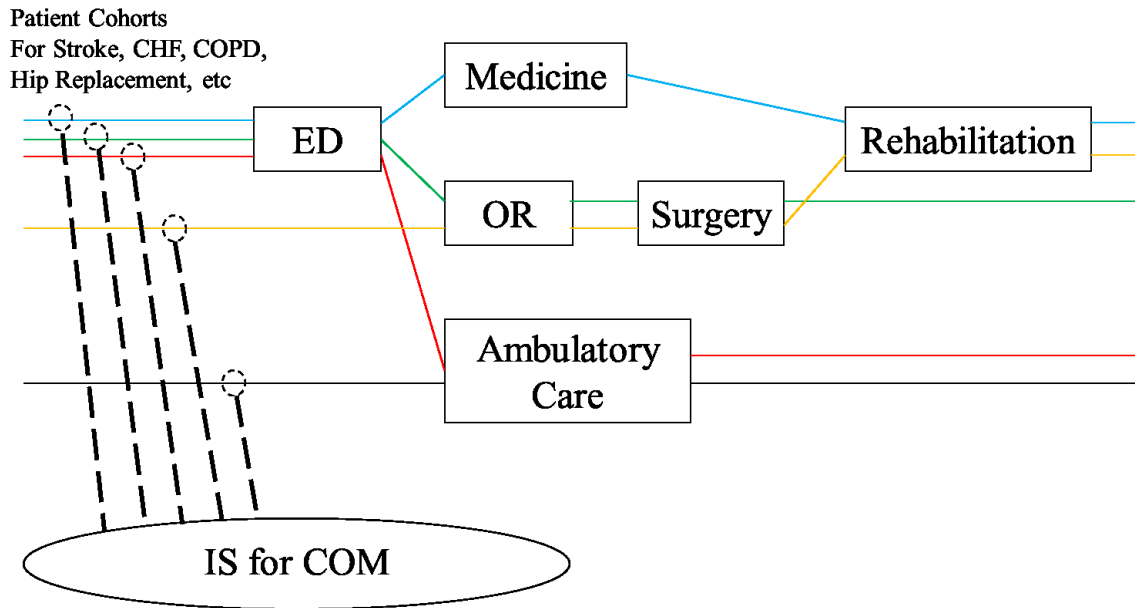


Figure 3-2 Patient-centered Focus of Hospital IS in Value-Based Hospitals

The problem our research is addressing is how to design the model-based information system for COM such that the hospital transformation towards a value-based hospital is facilitated and done in a more systematic, tool-supported, holistic, and effective manner.

3.2 Gap Analysis

In this section, we analyze current practice to highlight the critical gaps that need to be addressed. We also highlight to what extent that related work has attempted to address these gaps.

3.2.1 Current Practice

The AMIA EHR2020 Task Force [AMIA2020] has identified gaps in current Healthcare information systems such as lack of enterprise architecture and tools to guide the transformation. This is exacerbated by information systems that work in silos, do not collect the needed data, cannot process it in real-time, and do not give enough financial visibility to the Clinical Managers for them to make sound decisions based on data.

Other reports [IOM2012, AHA2011, TJC2008] also show that COM processes do not plan for data collection to support decision-making, and there is a lack of information system to produce real-time performance metrics; the information is not tailored to support decision-making, thus creating a cognitive load mismatch for the Clinicians.

For value-based hospitals, the current COM information systems, mostly from TeleTracking and Medworxx, are:

- Focusing on Patient Flow Management, Bed Management, Performance Management
- Designed for units, by medical specialties, but able to provide end-to-end coverage of clinical services
- Aiming at increasing hospital productivity
- Real-Time
- Integrated, within the Vendor suite
- Not enough patient-centric; they have no concept of patient cohorts
- Not enough aligned with Clinician workflows
- Not able to manage and customize clinical processes
- Not providing significant decision support to Clinicians
- Not sufficiently customizable from one hospital to another

Also, compounding the problem, there are:

- No real enterprise architecture driving the COM information systems
- No COM domain models to structure the knowledge
- No software development tools to accelerate the development of this next-generation COM information systems for value-based hospitals.

3.2.2 CHOIR Framework

The uTwente CHOIR Framework has attempted to address the gap of silos in healthcare, by proposing a framework for clinical operations in healthcare. The framework presented functional areas of healthcare management against decision levels. This framework does not cover functional areas like Performance Management, Human Resources Management, and Quality of Care, Risk and Safety Management; nor did it cover some orthogonal dimensions like Process, Structure, Event, Knowledge, and Organization, for instance. Another gap is the CHOIR Framework is structured to cover the Hospital Units, whereas the focus of a framework for value-based hospitals should be on patient cohorts and their journey through the entire hospital.

3.2.3 MPOWER

The MPOWER Architecture proposed a Model-Driven Engineering approach to Healthcare Information Systems. They are primarily targeting the IS and Technology Architectures of an Enterprise Architecture.

The strength of their platform is in the breadth of its capabilities, the end-to-end coverage of Homecare Services, and the very sound technical design approach. Gaps are in the lack of real-time operations, lack of decision support for the Clinicians in charge of delivering home care, and the models which are not at the Business Architecture level and therefore, require IS/IT knowledge.

3.2.4 DESSCOM

The DESSCOM project proposed an Object-Oriented Model-Driven approach to domain-specific information systems.

The strength of their system is in the object-based modeling and reasoning for Strategic and Tactical decision-making. Key gaps are in the absence of support for real-time operations, and lack of process management.

3.3 Validation Criteria

3.3.1 Enterprise Architecture for COM in value-based hospitals

A first set of criteria is about how well the Enterprise Architecture for COM is supporting the concept of value-based hospital. Most of the criteria either come from standards like Object Management Group Model Driven Architecture [OMG-MDA2014], Health Level 7 International (HL7), or The Open Group Architecture Framework [TOGAF], or they come from health organizations like the National Health Service in the UK [NHS2009], Ontario Ministry of Health and Long Term Care (MOHLTC) [QBP], Institute of Medicine [IOM2012], Healthcare Information and Management Systems Society [HiMSS-EMRAM], or American Medical Informatics Association [AMIA2020].

End-to-end coverage of services, QoC, compliance with QBP:

- End-to-end coverage of services: service line management; capacity assurance to meet demand. Criteria comes from MOHLTC.
- End-to-end Quality of Care: patient outcomes; quality assurance. Criteria comes from MOHLTC
- End-to-end compliance with QBP: Criteria comes from MOHLTC.
- Compliance with healthcare frameworks and ontologies: HiMSS EMR Adoption Model; ICD-10. Criteria comes from HiMSS.

Value-based performance management:

- End-to-end financial visibility: weighted case costing. Criteria comes from MOHLTC.
- End-to-end productivity increase: QBP reimbursement is based on average cost across province hospitals; this average decreases every year. Criteria comes from MOHLTC.
- Opportunity Analysis based on catchment area needs: population health management of hospital catchment area. Criteria comes from NHS.

Patient-centered care:

- Concept of patient cohorts; concept of service lines; smooth care transitions from unit to unit. Criteria comes from MOHLTC.

Integrated solution:

- Functional integration: process, capacity, performance, supply, QoC, Accounting, HR. Criteria comes from [Hans2011].
- Process integration: patient co-morbidities. Criteria comes from NHS
- Care transitions from Unit to Unit. Criteria comes from MOHLTC
- Interfaces with existing hospital information systems. Criteria comes from HL7 standards.

Real-time solution:

- Real-time operations management: real-time availability of data, of performance indicators; real-time patient tracking; real-time decision-making. Criteria comes from NHS and hospital staff.

Clinician-friendly solution:

- Alignment with clinician workflows: decrease cognitive load on Physicians; increase productivity of clinicians. Criteria comes from IOM.

Transformation to value-based hospital:

- Support for organizational transformation: the hospital enterprise architecture should support the changes in organization required by a major transformation; for instance, the move towards a matrixed organization. Criteria comes from OMG MDA, TOGAF, and hospital staff.
- Support for process transformation: the hospital enterprise architecture should support major clinical and administrative process improvements required by the transformation. Criteria comes from NHS, OMG MDA, and TOGAF.

Customizable solution:

- Customizability of COM information system for each hospital: the majority of requirements for COM information systems are common from one hospital to another

(these are the target of IS vendors); for the other requirements, customization to adapt to local guidelines, policies, and care pathways, is critical. Criteria come from hospital staff and executives at hospitals where I have worked.

Support for the main clinical operations functions:

- Support for the management of clinical operations in a hospital. Criteria comes from NHS.

Support for decision-making:

- Support for Strategic, Tactical, and Operational decision-making. Criteria comes from NHS
- Decision support capabilities: real-time patient flow management; decrease cognitive load on Physicians and Nurses. Criteria comes from IOM, NHS, and from hospital staff.
- Predictive analytics capabilities: accurate forecasts for next 24h in order to smooth patient flows and bed occupancy. Criteria comes from NHS.

3.3.2 Tool Support for Model-Driven COM in Value-Based Hospitals

A second set of criteria relates to the Model-Driven Engineering approach and how well the tools of our COM Platform (COMP Tools and COSBench) support Model-Driven COM in Value-Based Hospitals. Most of these come from OMG MDA and TOGAF, although some come from hospital staff we have interacted with:

Domain-specific, customizable models:

- Domain-specific models for entire hospital: models of hospital COM, from multiple views. Criteria comes from OMG MDA
- Customizability of models for each hospital: since for some requirements on hospital information systems, customization to adapt to local guidelines, policies, and care pathways, is critical, the models driving these information systems must be customizable also. Criteria comes from hospital staff.

Modeling by Clinicians:

- Clinician-friendly models: Clinicians should be able to create/edit these models by themselves, for their hospital. Criteria comes from hospital Clinicians.

Leverage existing standards & tools:

- Compliance with modeling standards: Criteria comes from OMG MDA.
- Synergy between MDE and TOGAF Enterprise Architecture: the models and tools should leverage the MDE-TOGAF synergy points as described in section 2.4.2. Criteria comes from OMG MDA and from TOGAF.
- Compatibility with modeling tools: There is a wealth of modeling tools available on the market. A domain-specific modeling language would have a higher chance of being adopted if it is compatible with those tools. Criteria comes from OMG MDA.

Enabler for decision support:

- Enabler for COM Decision Support Systems: the models and tools should enable the creation of COM Decision Support Systems. Criteria comes from IOM and hospital staff.

Integrated tool suite:

- The MDE approach covers the end-to-end transformation from models to code; therefore, the modeling tools and the code generation tools should be integrated. Criteria comes from OMG MDA.
- Weaving of models of different types, if needed: the experience from other industries about model-driven transformation is that usually more than one modeling language is required to represent all the complexity of the domain; therefore, the weaving of these different models into a coherent whole is critical. Criteria comes from OMG MDA.
- Code generation capabilities: There is a wealth of code generation tools available on the market. A domain-specific modeling language would have a higher chance of being adopted if it is compatible with those tools. Criteria comes from OMG MDA.

3.3.3 Use of Validation Criteria

The above criteria will be used in Chapter 6 in order to evaluate the COM Platform and assess how well it has met the research objectives, and what remains to be done in future work.

4 Enterprise Architecture for Model-Driven COM in Hospitals

In this chapter, we present a platform for model-driven Clinical Operations Management (COM) in hospitals. The context for this platform is an understanding of the enterprise architecture that hospitals need in order to transform themselves into value-based hospitals. Our focus is to support this transformation with a model-driven platform for generating Clinical Operations Support Systems (COSS) that support value-based hospitals.

4.1 Overview

4.1.1 COM Platform

Figure 4-1 shows the key components of our proposed COM platform.

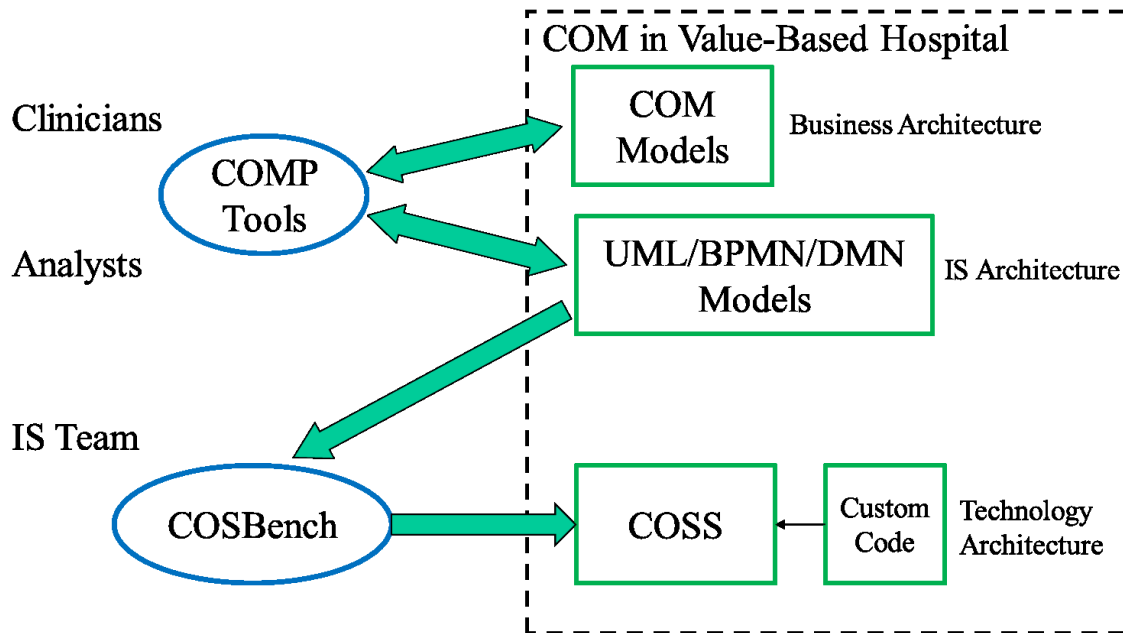


Figure 4-1 COM Platform

Each of the blue circles and green rectangles is described in detail in its own section of this chapter.

The blue circles represent the model-driven tools in the platform that are used by Clinicians and Analysts to transform from models to models and by the IS Team to generate software from models:

- COMP Tools for modeling
- COSBench for code generation

The dashed box represents the enterprise architecture of a value-based hospital as it relates to COM, and each of green boxes shows the models or software that are relevant at the three levels of the enterprise architecture:

- COM Models at the business architecture level;
- UML/BPMN/DMN Models at the information systems (IS) architecture level;
- COSS Modules generated by the platform (with supplementary custom code) at the technology architecture level.

The COM Models conform to COMP, a Domain-Specific Modeling Language, which is a UML Profile. Figure 4-2 shows the model transformations, until the COSS is generated.

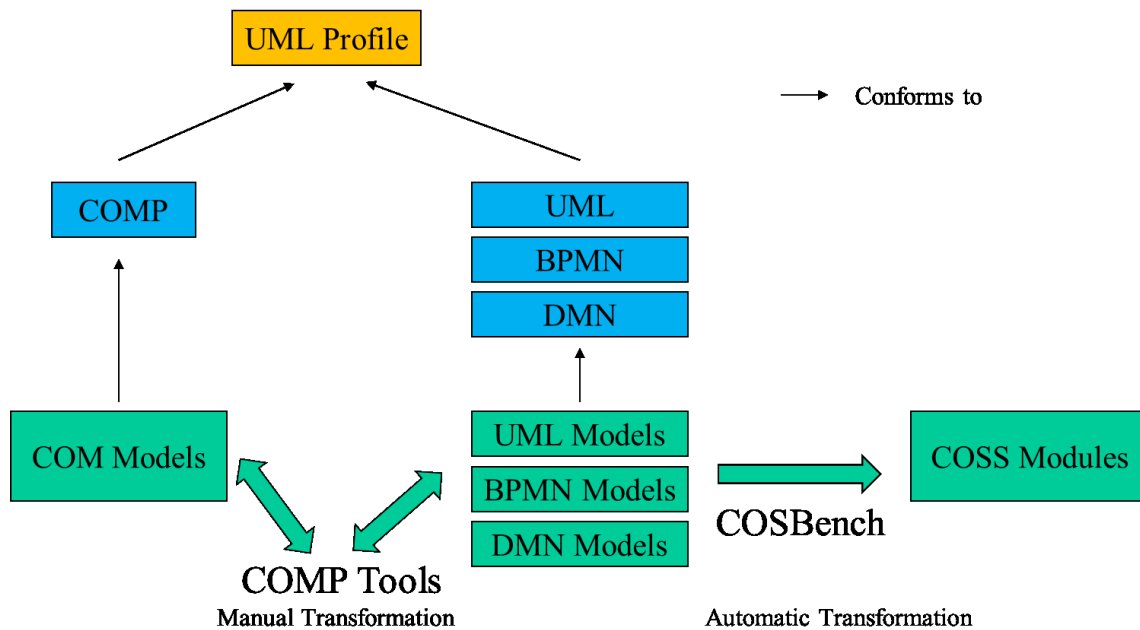


Figure 4-2 Model Transformations in MDE

The COM Platform is composed of the following:

COMP Tools:

They are used to build the COM Models and the UML/BPMN/DMN Models.

- The Clinical Operations Management Functions Table (COMF) which organizes the COM models in terms of functions as well as levels of decision-making.
- The Clinical Operations Management Profile (COMP), which is a Domain-Specific Modeling Language with associated model libraries, that is used to specify COM models. Even though COMP is a language, not a tool, and it is used to specify, not to transform, we chose to keep it in the group of COMP Tools because they all depend on it.
- The COMP Modeling Tool, which is used by Clinicians to create COM models for a specific hospital. The COM Models are then manually transformed into woven UML/BPMN/DMN models by Analysts.
- Engineering tools for optimization, simulation, and Multi-Criteria Decision Analysis.

COM Models:

The goal for COM Models is to represent the set of clinical services supported by administrative services for the care of a specific group of patients, a cohort, as represented in the Figure 4-3 COM Enterprise Architecture Diagram below. Therefore, the COM Models directly support the concept of Service Line Management in value-based hospitals.

The COM Models are patient-centric, that is, they are organized to describe what is needed and what has to happen end-to-end for a cohort of patients to get optimal care in the Service Line.

Conforming to the TOGAF standard for enterprise architecture [TOGAF], the COM Models are structured along 7 views as illustrated with example models in Figure 4-3 below: Function, Process, Structure, Event, Knowledge, Organization, and Engineering. Figure 4-3 is a diagram we have defined, called the COM Enterprise Architecture Diagram. Each hospital will determine what models are relevant for their COM in terms of these 7 views.

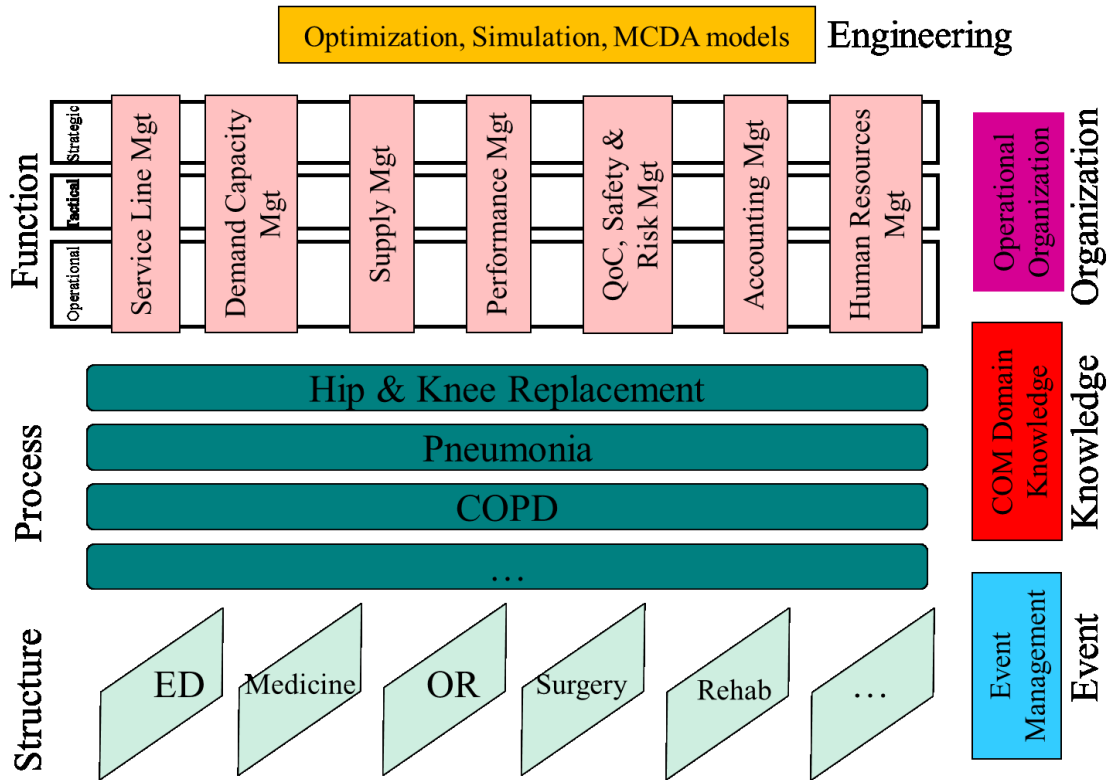


Figure 4-3 COM Enterprise Architecture Diagram

The COM Models are at the highest TOGAF level of modeling, the Business Architecture, and are intended to be built by Clinicians with a good understanding of Clinical Operations and how they should be managed. The COM Models are defined using COMP, a Domain-Specific Modeling Language we have created. They are used as a foundation to build and customize the UML/BPMN/DMN Models with the COMP Modeling Tool.

UML/BPMN/DMN Models:

The UML/BPMN/DMN Models are a more detailed version of the COM Models at the Information Systems level in the TOGAF Enterprise Architecture. They are built by Analysts trained in Clinical Informatics. The UML Models also include the Clinical Operations Object Model (COOM), which is an UML object model used as blackboard data structure by the COSS at run-time. This allows the different applications and subsystems of the COSS to share model-defined data in a structured way. The UML Models

also include models defined using Service Oriented Architecture Modeling Language (SOAML) which help define the existing service architecture of the hospital and HL7 message protocols that must be used by the generated COSS.

COSBench:

COSBench is a code generation toolkit for generating COSS Modules. It enables software engineers to transform woven UML/BPMN/DMN models into the COSS modules that support Clinical Operations Management.

COSS:

A Clinical Operations Support System (COSS) is an architecture of software modules that support an end-to-end, real-time, patient-centered management of clinical services, in alignment with Clinicians' workflows. It is a layer of custom software that is generated for a particular hospital based on the COM models defined by that hospital while targeting the existing service-oriented architecture of off-the-shelf software that exists at the hospital. The customized COSS for a specific hospital is created by:

- customizing COM Models;
- transforming them into UML/BPMN/DMN models; and
- generating COSS modules.

Some custom Java code might need to be added or modified in the COSS modules. The COSS modules use a shared blackboard data structure for decision support.

4.1.2 COM Enterprise Architecture, TOGAF, and Model-Driven Engineering

As described in chapter 2, the Model-Driven Engineering approach consists of a series of model transformations until the final information system is generated. From a Computing Independent Model (CIM), a first transformation is made in order to get a Platform Independent Model (PIM). Then, another transformation is applied to get a Platform Specific Model (PSM) which leads to the code generation.

The CIM maps roughly into the TOGAF Business Architecture.

The PIM maps roughly into the TOGAF IS Architecture.

The PSM maps roughly into the TOGAF Technology Architecture.

The CIM-to-PIM model transformation is done mostly manually with the COMP Tools, whereas the PIM-to-PSM transformation is done with COSBench.

This is described in the table below:

Table 4-1 COM Enterprise Architecture, TOGAF, and Model-Driven Engineering

TOGAF Layers	COM EA	MDE	Artifacts
Business Architecture	COM Models	Computing Independent Model	Business Architecture in COMP
	 COMP Tools		
Information System Architecture	UML/BPMN/DMN Models	Platform Independent Model	- Services in SOAML - Components in UML - Processes in BPMN - Rules in DMN
	 COSBench		
Technology Architecture	COSS modules	Platform Specific Model	- JEE Modules - jBPM2 models, for instance - DROOLS rules, for instance

4.1.3 COM Enterprise Architecture and the Research Question

The Figure 4-4 Model-Driven COM in a value-based hospital below is a further refinement of Figure 1-1 Model-Driven Engineering of COM in value-based hospitals that shows in more detail how the COM Platform addresses our Research Question in the

context of the transformation towards value-based hospitals. The COM Models are generated by Clinicians using the COMP Tools, and are transformed by Analysts into UML/BPMN/DMN models. The COM Models provide clear definitions and guidelines for People, Process, and IS/IT redesign (shown by dashed lines) and the UML/BPMN/DMN Models, using COSBench, can be used to generate a COSS that supports Clinical Operations Management in a value-based hospital.

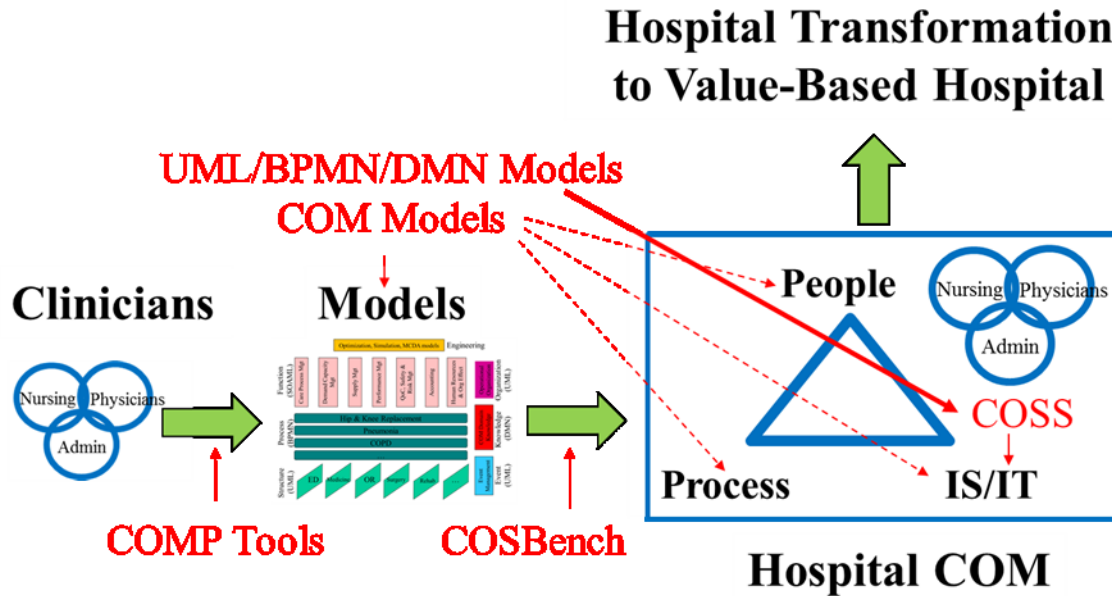


Figure 4-4 Model-Driven COM in a value-based hospital

It should be noted that the COM Models can also be used without COSBench and the COSS, in order to drive the redesign of the hospital processes and organization, independently of the information system and information technology supporting them. In other words, the COM Models built using COMP Tools define Clinical Operations Management for the hospital. They can be used on their own to guide improvements and business transformation towards a value-based hospital. This is one contribution of our thesis.

Generating a COSS using COSBench is a model-driven engineering approach for building information technology support of COM. This is the second contribution of this thesis.

4.1.4 Examples: Cardiac Procedures and Joint Replacement service lines

Based on the case studies in section 5.2 and 5.3, two examples are going to be used throughout this chapter:

- Cardiac Procedures Service Line
- Joint Replacement Service Line

Cardiac Procedures take place in a Cardiac Catheterization Lab, and their goal is to improve and re-establish the vascularization of the heart. The build-up of plaque in the heart arteries blocks the blood flow and leads to heart attacks. The procedures consist in introducing a catheter in the heart arteries, taking pictures in order to establish a diagnosis (Angiogram), and if required, widening the artery (Angioplasty) and leaving a stent in place (Stenting) to prevent the artery from narrowing again.

Joint Replacement is a surgical procedure to replace a dysfunctional, painful hip or knee joint with an orthopedic prosthesis, thus giving back to the patient normal limb mobility.

In Section 4.3, a set of COM models is described. In Section 4.4, a corresponding set of UML/BPMN/DMN models, including COOM and SOAML models, is described. Finally, in Section 4.6, the generated COSS modules supporting the examples and the overall COSS architecture are presented.

The examples of COM Models and COSS Modules for the Joint Replacement and Cardiac Procedures Service Lines are the third contribution of this thesis.

4.2 COMP Tools

The COMP Tools are used for building COM Models and UML/BPMN/DMN Models, as shown in Figure 4-5 below. In several iterations, they enable a Clinician to build COM Models from scratch or from examples (in section 4.1.4), according to the 7 views of Figure 4-3 COM Enterprise Architecture Diagram. These models are then stored in the Repository. An Analyst, working closely with the Clinician, then builds UML/BPMN/DMN Models, based on the COM Models, and stores them in the Repository.

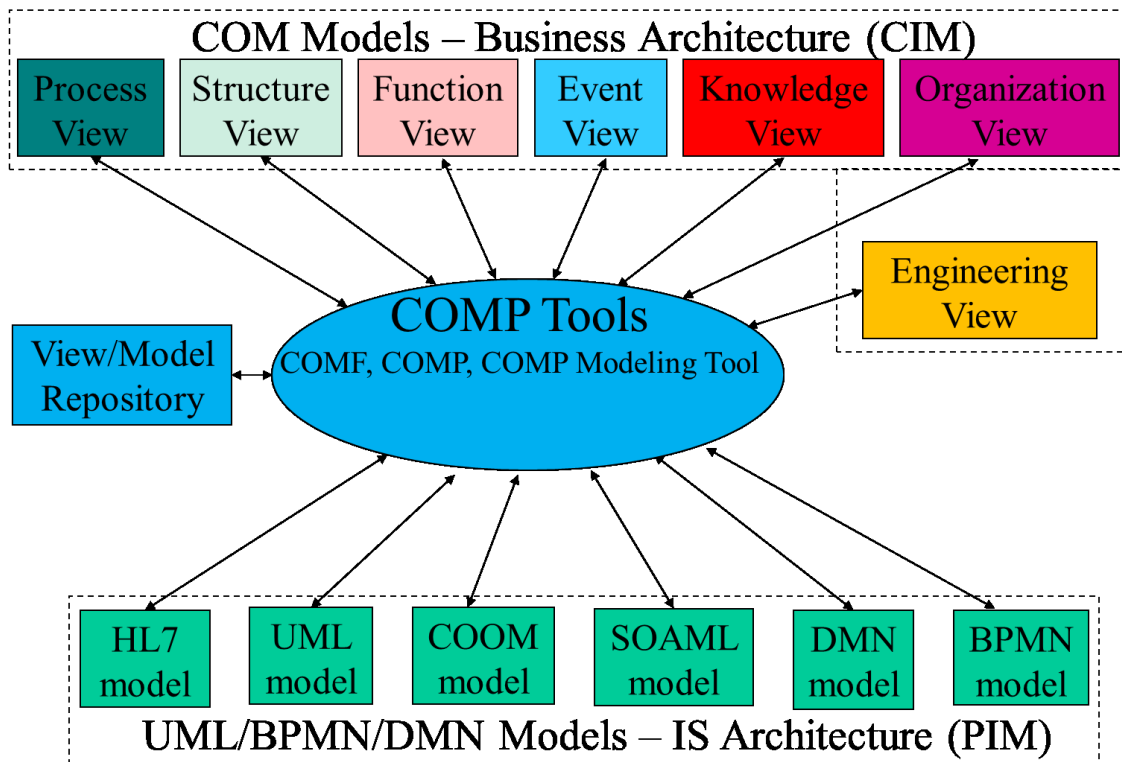


Figure 4-5 COMP Tools

4.2.1 COMF

COMF helps structure more the COM domain knowledge and guide the creation of a set of COM Models. It defines a set of clinical operations management functions common to most hospitals, and the timespan when they are applicable. These functions also provide

support for decision-making. We have created a COM Functions Table to communicate this information. See Table 4-2 COM Functions Table in a value-based hospital below.

Our COM Functions Table has extended the uTwente CHOIR framework (Section 2.6.2) with additional columns: Service Line Management, Performance Management, Human Resources Management, and QoC, Risk, and Safety Management. We have also modified Medical Planning because the Strategic and Tactical levels as described in the CHOIR framework are usually covered by the Physicians outside of the COM domain. The activities and types of decisions at each level have been defined.

The columns of the COM Functions Table describe all the functional areas of the COM domain, and they provide the basis for the Function View of the COM Models (see section 4.3.4).

The COM Functions Table is used to guide Clinicians when building COM Models. It shows all the COM Functions and what they do in a value-based hospital, in order to ensure that no Function is overlooked when the COM Models are built. Similarly, the COM Functions Table is also used to guide the Analyst when building the UML/BPMN/DMN Models; it shows the possible links between all the Functions and guide the detailed modeling.

The rows of the COM Functions Table indicate the decision-making level (Strategic, Tactical, Operational), and hence the lifespan and impact of the decision (from years to minutes). The Strategic and Tactical decisions are supported by the engineering models and tools described in section 4.3.10. The Operational decisions are about day-to-day operations, and are supported by the COSS described in section 4.6. The Operational Online decisions are made in real-time, whereas the Operational Offline decisions could have a lifespan of several days. The table helps the Clinician building COM Models to understand how the Strategic, Tactical, and Operational decisions are linked to each other and how they impact each other.

Table 4-2 COM Functions Table in a value-based hospital

COMF	Service Line Management	Demand Capacity Management	Performance Management	Quality of Care, Safety, and Risk Management	Supply Management	Accounting Management	Human Resources Management
Strategic (1-3 years)	Selection of Care Pathways and QBPs based on service mix and case mix	Service mix planning; Case mix planning; Capacity dimensioning; Workforce planning	Performance Management policies	QoC Policies; Culture of Safety; Accreditation	Supply Chain design; Materials Planning	Investment plan; Annual Budget	Organization structure; Workforce planning; Roles & responsibilities
Tactical (3-6 months)	Planning of care processes implementing customized Care Pathways and QBP for patient groups	Master Surgery Scheduling; Shift Scheduling; Scoping Ancillary Services	Performance Management planning; Historical Performance Analysis & Reporting	QoC Reviews; Risk Management; Falls prevention; Infection Control policies	Supplier selection; Tenders; Procedure Card mgt	Budget tracking; Activity Based Costing; analysis	Hiring; Training; Change mgt; LEAN deployment
Operational - offline (1-4 weeks)	Care Plan for individual patient; Activity plan update	Appointment scheduling; Booking; Staffing; Admission Control	Operational Performance Forecasting (operational BI)	Infection Control; High-risk medication management	Stock purchasing; Non-Stock ordering	Billing; Cash-Flow analysis; Financial Control	Staffing; Workforce Mgt; Continuous improvements
Operational - online (real-time; daily)	Care Plan update in real-time; Activity management; Process Monitoring & Control	Capacity monitoring & control; Full-Capacity protocol; Staffing-to-Census; Real-Time Patient Flow Mgt; Housekeeping & Portering	Performance Monitoring & Control; Escalation management	Adverse Event monitoring & control; Escalation management	Inventory Control; Rush ordering; Unit inventory replenishing	Overtime tracking; Support for staffing-to-census	Sick time tracking; Support for staffing-to-census; Real-time staffing

The following gives an overview of the 7 functions.

Service Line Management (SLM):

Service Line Management is about provisioning the clinical and administrative services for a given patient, delivering the care to the patient, and then monitoring the quality of service.

Provisioning the services entails ensuring that capacity is available for the specific demand of the patient. It uses the Demand & Capacity Management function.

Monitoring the quality of service uses the Performance Management function.

At the Strategic and Tactical level, the creation design, and implementation of the services or service lines is described below, in the Engineering View.

At the Operational level, service management is about managing the Care Plan for the individual patient, update it in real-time, coordinate the activities of the Care Team for the individual patient on a specific Care Pathway, and monitor the care process.

Demand & Capacity Management (DCM):

Demand & Capacity Management deals with smoothing the patient demand for care whenever possible, and matching it with optimal hospital capacity. At the Strategic level, it involves quantitative planning of the service mix and case mix, and dimensioning of the hospital capacity needed to deliver the service mix for the case mix. At the Tactical level, this translates into the scheduling of Nursing and Physician shifts, the Master Surgery Schedule, the scoping of Ancillary Services, for instance: that is the allocation of a group of resources to a group of tasks. The demand smoothing and admission control is done at the Operational offline level with the booking of elective surgical procedures, the admission of elective Medicine patients, for instance. The capacity allocation at the Operational level deals with the staffing of individual Nurses, the scheduling of

individual Physicians, the staffing-to-census on the wards, the real-time patient flow management, the Full-Capacity Protocol activation, the real-time allocation of Housekeeping and Portering resources.

Examples of Demand & Capacity Management functions:

- Demand Smoothing;
- Demand Prediction;
- Capacity Scheduling;
- Capacity Allocation;
- Master Surgery Scheduling;
- End-to-end Patient Flow Management

Performance Management (PM):

Performance Management in the context of COM is about policies at the Strategic level, translating into planning and historical performance analysis & reporting at the Tactical level. At the Operational level, there is performance forecasting used in parallel with performance monitoring & control; in case of problems, surges or activation of the Full-Capacity Protocol, there is also escalation management. The Operational Business Intelligence is a promising emerging technology in COM, which gives real-time visibility on performance at the individual patient or Clinician level.

Examples of Performance Management functions:

- Performance measurement
- Performance event notifications (collection, filtering, processing)
- Real-time performance analysis
- Support to real-time decision-making
- Historical performance reporting

Examples of Performance Indicators:

- Pre-Op
 - Wait Time 1 (Primary Care Physician-to-Consult)
 - Surgical Yield
- OR/InPatient
 - Wait Time 2 (Consult-to-Procedure)
 - Acute Length-of-Stay
 - Discharge Disposition
 - Sub-Acute/Stepdown Length-of-Stay
 - Intra-Op Adverse Events
 - Acute Care Adverse Events
 - Total OR Time
 - Turn Over Time
- Post-Op
 - Patient Outcomes
 - Adverse Events within 30 days post-op
 - Revision Rate within Year 1
 - Patient Satisfaction
- Key Performance Indicators
- Outcome vs Process Indicators
- Real-time performance monitoring & control
 - Procedure Cancellations
 - Delays in case starts
 - OR over-utilization
 - Bed Occupancy
- Accounting indicators
- Process indicators
- Demand indicators
- QBP Patient Flow indicators
- Supply Chain indicators
- Staffing indicators

- QoC indicators

Supply Management (SM):

Supply Management deals with supply chain design and materials planning at the Strategic level; this impacts all units of the hospital, starting with the ORs. At the Tactical level, it involves the selection of vendors supplying the units. There is also the management of the Procedure Card to ensure that every needed supply is available for a given procedure performed on a group of patients. At the Operational level, this translates into near real-time management of inventory levels, ensuring for instance that the joint implant of the right type and size is available on day D at time T for a joint replacement procedure performed by Surgeon X on Patient Y.

Examples of Supply Chain Management functions:

- Case cart management
- Procedure card updates
- Inventory management of implants
- Monthly re-stocking procedure
- Rush ordering procedure

Quality of Care, Safety, & Risk Management (QoCM):

Quality of Care (QoC), Safety, & Risk Management is a key COM functional area dealing with hospital quality problems. At the Strategic level, it deals with QoC policies, with instilling a pervasive culture of Patient and Staff Safety, with the hospital QoC accreditation process. At the Tactical level, this translates into QoC reviews, after a quality problem has been identified, of the design of QoC improvements, and the prevention of falls, infections, or other adverse events. At the Operational level, it involves the near real-time monitoring & control of adverse events, the escalation management, and the management of high-risk medication.

Examples of QoC, Safety, & Risk Management functions:

- Quality management; root cause analysis
- Surgery adverse event management
- Surgery infection control

Accounting Management (AM):

Accounting Management in the context of COM is to give the hospital the capability of real-time monitoring of its costs on a per procedure basis, end-to-end across the entire hospital. This is a concept taken for granted in other industries, but relatively new to hospitals. This requires budgeting at the Strategic level, done not only per unit but also per procedure type, and Activity-Based Costing at the Tactical level. This is supported by real-time accounting data acquisition, analysis, and reporting at the Operational level.

Examples of Accounting Management functions:

- Service Line Reporting
- Weighted Case Costing
- Patient-level information and costing
- Accounting Event analysis

Human Resources Management (HRM):

Human Resources Management in the context of COM is about workforce planning at the Strategic level. At the Tactical level, this functional area deals with hiring, training, leading Change across the hospital, and deploying LEAN. At the Operational level, this translates into real-time staffing in the units based on the patient demand, monitoring of sick-time, providing support to LEAN improvements.

Examples of HR Management functions:

- Absenteeism analysis

- Real-Time Staffing
- Support to Staffing-to-Census

The following gives an overview of the decision-making levels.

Decision level: Strategic

These are decisions typically made by the Senior Leadership Team (CEO, VPs) of the hospital, about the creation of new clinical services and resources to be allocated. These decisions involve groups of individuals and groups of services. Their granularity is high-level. The timespan is typically 1 to 3 years.

Decision level: Tactical

These decisions are typically made by Clinical/Medical Directors. The timespan is typically 3 to 6 months. The decisions are about individual services, but still about groups of Patients and Clinicians.

Decision level: Operational Off-line and On-line

These decisions are typically made by front-line Staff and by their Managers. The timespan is real-time (on-line) and 1 day to 1 month (off-line). The decisions are about individual Patients and Clinicians.

Interdependencies between Functions

As can be seen above, there is a lot of interdependencies between the COM Functions, and only a holistic approach to their specification could realistically reflect their richness and complexity.

- SLM, DCM, and PM are tightly interconnected. They are the core functions. The best way to untangle these interdependencies is to start with the design of the care process. The design will identify the clinical services and the patient cohorts

- (SLM). It will highlight where some resources will have to be assigned (DCM), and where performance events have to be generated in order to enable the processing of performance indicators (PM). It will also highlight where in the process events have to be consumed (from DCM and PM) which might impact the process task sequencing; these are often decision nodes in the process diagram.
- SM is interdependent with DCM. The supply chain is designed to meet the needs of one type of resources managed by DCM: the supplies, implants, consumables. It is therefore driven by DCM. Conversely, SM has to notify DCM when there is an inventory problem and no short-term solution to it, such that DCM can pursue a fallback path.
 - QoCM should notify SLM, DCM, and PM when there is a fault or adverse event which may respectively impact the care processes and/or capacity management and/or the performance indicators. Conversely, a problem seen by SLM might be a symptom of an adverse event which would require a QoCM root cause analysis.
 - AM needs finance-related events which enable the processing of accounting indicators. These are generated mostly by care processes, by the allocation of resources to a Patient and/or Clinical Service (SLM) and from performance events (PM).
 - HRM is dependent on resource allocation events (DCM) about staffing. Conversely, it could generate events about staff availability which might impact DCM.

Salient features of the COM Functions Table

- The table shows that, at the Strategic and Tactical levels, we deal with decisions that impact groups of patients and groups of Clinicians, whereas at the Operational level, we deal with decisions impacting an individual patient and/or an individual Clinician.
- Each level is impacted by the level above, and directly impacts the level below.

- There are strong inter-dependencies between the functional areas.

Benefits of COM Functions Table

Currently, Service Line Management is done mostly manually, in an ad hoc way. The COM Function Table supports the hospital organization in providing a framework for roles & responsibilities, and ensures that all functional aspects of Service Line Management are considered.

The COM Functions Table is also used to guide the next steps of COM modeling as seen in the next sections.

To summarize, the COM Functions Table provides a framework for the hospital organization, for the redesign of care processes, and for the development of COSS. These are the critical components of hospital transformation.

Some examples of use of the COM Functions Table are given in Appendix A.

4.2.2 COMP and its MetaModel

COMP is a Domain-Specific Modeling Language used to build COM Models. It targets the Business Architecture layer of the TOGAF Enterprise Architecture. COMP conforms to its MetaModel which is a UML profile defining stereotypes for the 7 Views described in Figure 4-3 COM Enterprise Architecture Diagram (section 4.1.1), and for clinical concepts like Clinical Service, Service Line, Patient Cohorts.

Figure 4-6 below is an overview of the COMP MetaModel according of the 7 views. Its purpose is just to give a sense of the overall complexity. More detailed, and readable, figures for each View of the MetaModel follow after Figure 4-6.

It has to be noted that the top-level stereotypes (Function, Process, Structure, Event, Organization, Knowledge, Engineering) are abstract, and only their sub-classes (Service Line Mgt, Clinical Unit, QBP, etc) can be instantiated.

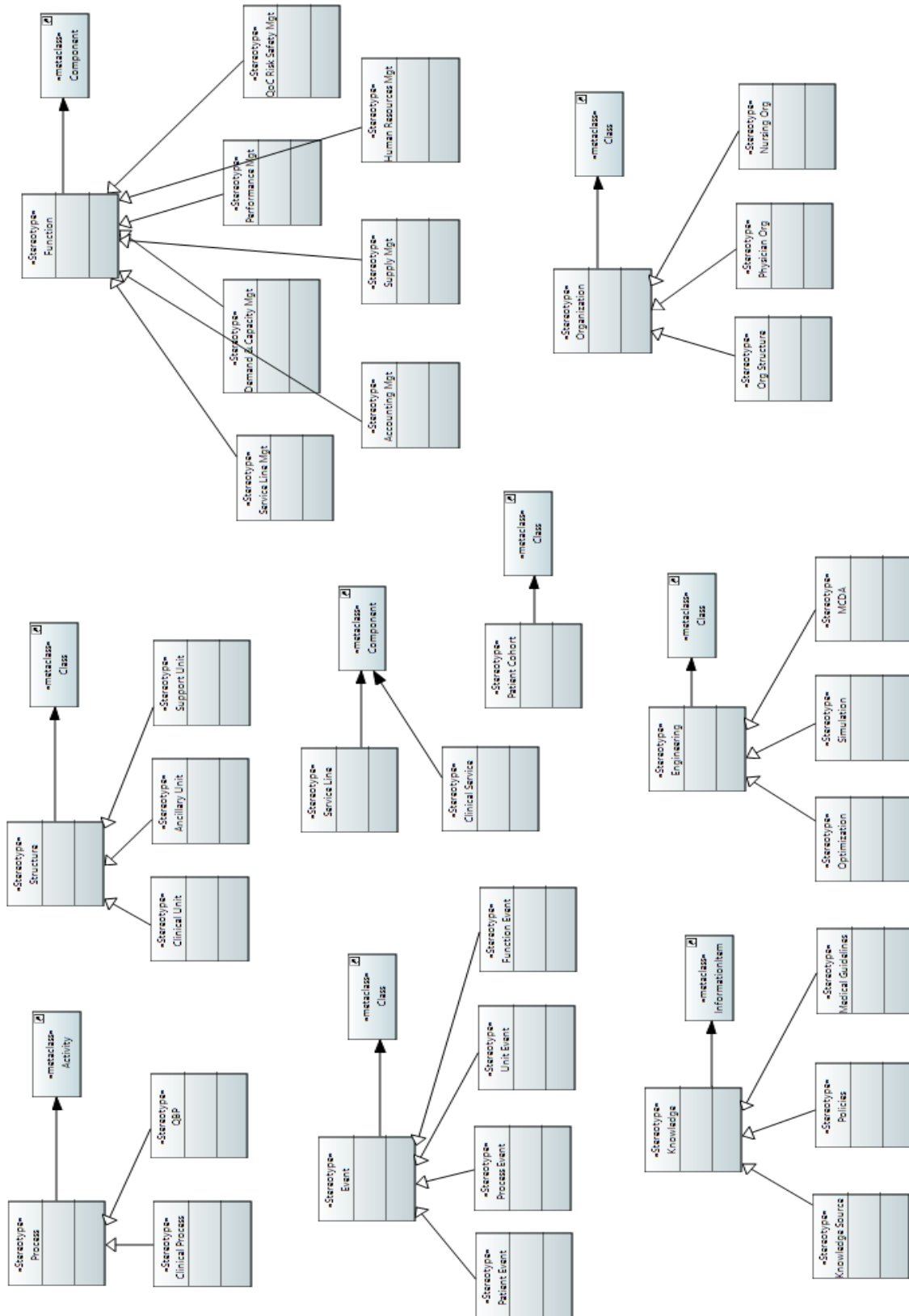


Figure 4-6 COMP MetaModel Overview

The figures below show the stereotyping of the 7 views:

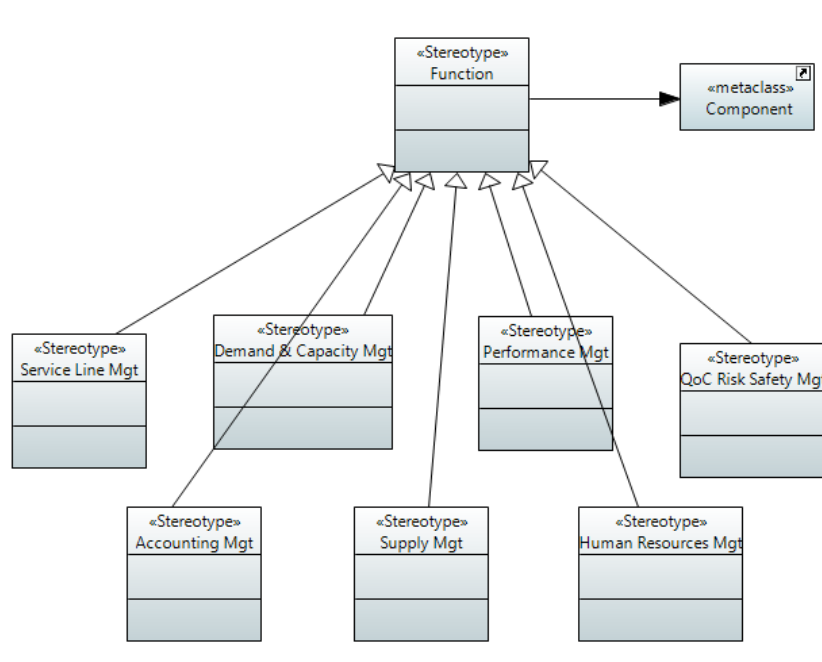


Figure 4-7 COMP MetaModel for the Function View

The functions in Figure 4-7 above are derived from the COM Functions Table columns. They are stereotyped with a MetaClass <<Component>>, instead of <<Class>> like most of the others, simply to give more flexibility to the Clinician doing the COM modeling to explicitly show services that these functions provide to each other at this abstraction level, if needed. We prefer to show these services in the SOAML modeling, described in section 4.4.1.

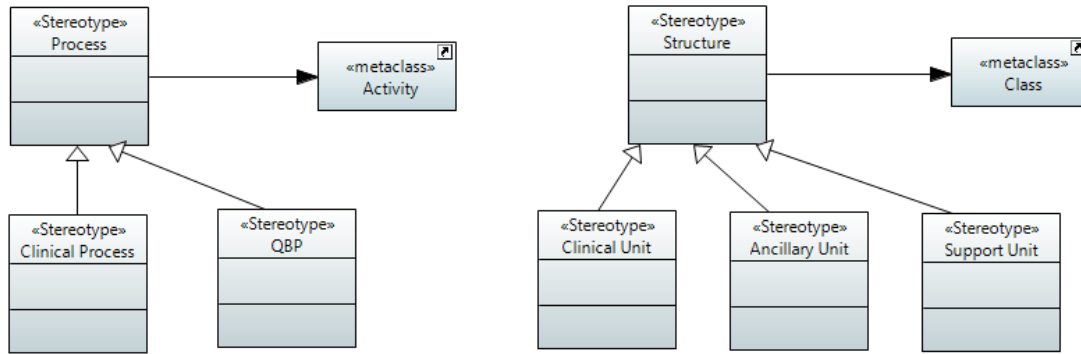


Figure 4-8 COMP MetaModel for the Process and Structure Views

The clinical processes and QBPs in Figure 4-8 above are usually described in text, as in sections 5.2.1 and 5.3.1, at this stage of modeling. However, we have decided to stereotype them with a MetaClass `<<Activity>>`, instead of `<<Class>>` like most of the other Views, in order to give more flexibility to the Clinician to build Activity diagrams if needed.

The units in the Structure View of Figure 4-8 are stereotyped `<<Class>>` in order to best capture their structure model. There are 3 types of Units:

- Clinical Units: Emergency Department, Operating Rooms, Medicine ward, Surgery ward, Rehabilitation Unit, etc.
- Ancillary Units: Diagnosis Imaging (for X-Rays, CT-Scan, MRI), Lab Unit (for blood test), Physiotherapy, Ergotherapy, etc.
- Support Units: Social Workers, etc.

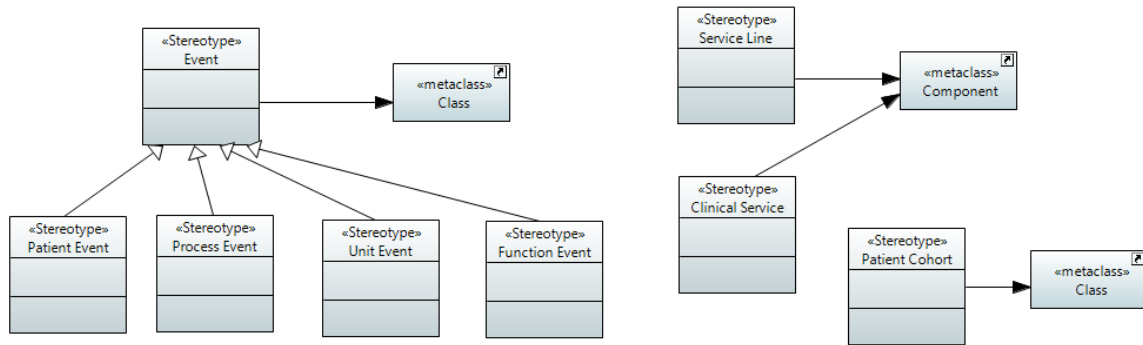


Figure 4-9 COMP MetaModel for the Event View and for Service Line

The event types in the Event View of Figure 4-9 above are stereotyped <<Class>> in order to best show their structure. Shown here are events about the Patient, the Process, the Unit, and the Function. There are other event types about the Environment (sensors), and the hospital business.

The Service Lines and Clinical Services in Figure 4-9 are stereotyped <<Component>> in order to give flexibility to the Clinician in showing how a service line is composed of a set of clinical services and other service lines, and how the collaboration is done, if needed. The service lines and clinical services are centered on the Patient Cohorts, which are stereotyped <<Class>>. These 3 concepts are central to hospital COM, and the 7 Views allow to explore their different dimensions.

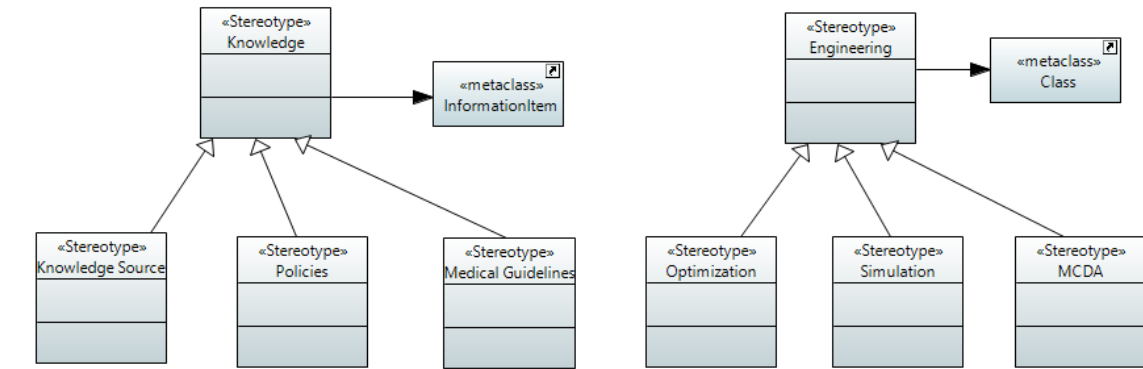


Figure 4-10 COMP MetaModel for the Knowledge and Engineering Views

The Knowledge Sources, Policies, and Guidelines in the Knowledge View of Figure 4-10 above are stereotyped <<InformationItem>> for flexibility. The Engineering Tools for Optimization, Simulation, and MCDA in the Engineering View of Figure 4-10 are stereotyped <<Class>> in order to focus on their operations, the input parameters they need, and the output they generate. They are encapsulated in the object-oriented way because there are many different tools available on the market, and we only need to abstract them.

4.2.3 COMP Modeling Tool

The COMP Modeling Tool has the following main functions:

- Support COMP modeling, and the COM Models
- Support the UML (including COOM, SOAML and HL7), BPMN, and DMN modeling. This also includes the UML modeling required for the Engineering Views of COM Models.
- Support the manual transformation between these models
- Support the weaving of these models together
- Provide a repository for all models

The COMP Modeling Tool has been prototyped (section 5.4.1), and is a combination of several open source Eclipse tools; together, they provide the functions above.

The COMP Modeling Tool is used by Clinicians and Analysts in the following way:

- Clinicians first visualize the COM Models and their 7 Views (Process, Structure, Function, Event, Knowledge, Organization, and Engineering), using for instance the examples provided in section 4.3, and then customize them for their hospital.
- The Analysts then update the UML, BPMN, and DMN models accordingly.
- Finally, the models are woven back together by the Analysts.

A lab prototype of the COMP Modeling Tool is described in the case study of section 5.4.1.

4.3 COM Models

4.3.1 Overview

The Figure 4-11 below shows the Service Line Template for COM Models, with all stereotypes in place, that Clinicians could customize for their hospital, using concepts and knowledge they are used to, instead of an information system language. One objective of the COM Models is to be easy to use for the Clinicians; they are mostly declarative, using the clinical vocabulary. We have chosen to describe the COM Models and their relationships with text rather than comprehensive UML diagrams and associations because they are intended primarily for Clinicians.

The top of the template shows a Service Line, with Clinical Services and Patient Cohorts, but the template is centered on the Process View which is driving all the other views of a COM Model.

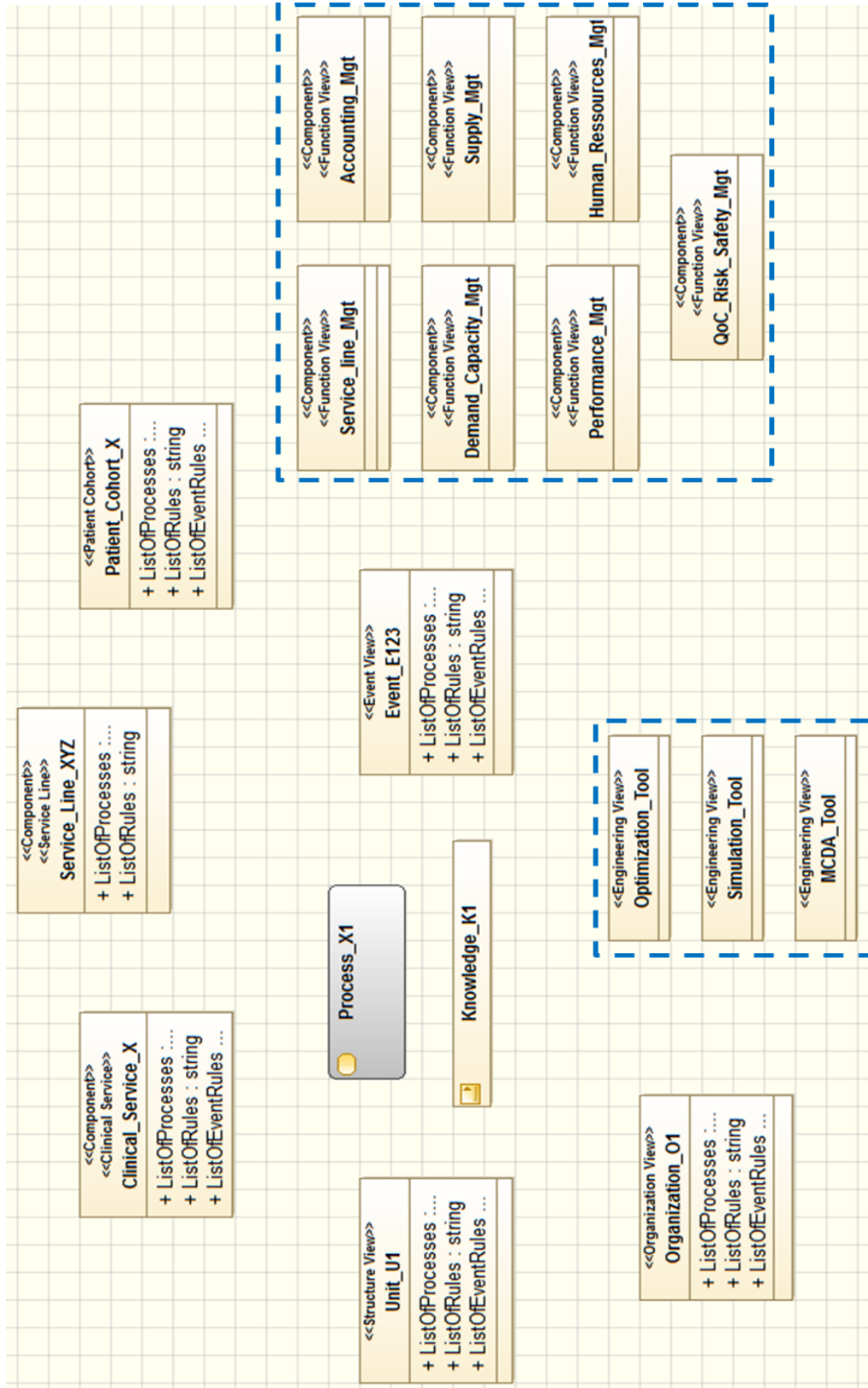


Figure 4-11 Service Line Template for COM Models

The Service Line, Clinical Service, and Patient Cohort model is required because they are central to COM.

As was shown in Figure 4-3 COM Enterprise Architecture Diagram (section 4.1.1), there are 7 Views in the COM Models: Structure, Process, Function, Event, Knowledge, Organization, and Engineering.

- The Structure View focuses on the physical organization of the hospital, particularly within the Service Line, with the units, rooms, beds, etc. The main class hierarchy is of type “Containment”.
- The Process View focuses on the description of the clinical processes and their operations. The hierarchy is typically composed of sub-processes.
- The Function View, shown inside a dashed blue box, describes the main COM functions in a hospital, based on the COM Functions Table columns, namely:
 - Service Line Management
 - Demand & Capacity Management
 - Supply Management
 - Performance Management
 - Quality of Care, Risk, and Safety Management
 - Accounting Management
 - Human Resource Management
- The Event View describes the structure and relationships between all types of events generated and notified during clinical operations
- The Knowledge View describes the formal and informal knowledge bases existing in the hospital, about its clinical operations. This includes policies and guidelines. The knowledge is encoded as a set of DMN rules in order to make it actionable. Some knowledge bases are used in the COSS blackboard system.
- The Organization View focuses on the main types of organization structure for a Service Line, and particularly how the Physicians and Nurses are organized.

- The Engineering View, shown inside a dashed blue box, is composed of the Optimization, Simulation, and MCDA tools, enabling the design and sizing of the Service Line.

Every hospital has COM Models with up to 7 views. The Function, Process, Structure, and Event views are mandatory. The Knowledge, Organization, or Engineering view, can be added later on.

And, every hospital has a Function View with up to 7 functions. It is highly recommended to model as many functions as possible, since this makes the COSS even more powerful.

A hospital does not have to model all their Service Lines with COM Models. They can start with one Service Line and then add others as needed. Adding service lines is fairly easy since they reuse existing COM Models.

One main benefit of COM Models is that they force the hospital to exhaustively and systematically plan their new service lines, and over time their transformation towards value-based hospitals. The Service Line Template for COM Models serves as guidelines in the transformation.

Table 4-3 below shows the dependencies that the Views have among themselves.

- Process and Function Views depend upon all other views.
- All views depend upon the Structure View.

Table 4-3 View Dependencies

	Process	Structure	Function	Event	Knowledge	Organization	Engineering
Process		D	D	D	D	D	D
Structure	D			D	D	D	D
Function	D	D		D	D	D	D
Event		D			D		
Knowledge		D		D			D
Organization		D		D	D		
Engineering		D					

D = Dependency that row has upon column

The Clinician doing the COM modeling would typically proceed as follows:

- Start with the Process View modeling, by entering the text and eventually diagrams of the QBP and/or Care Pathways describing the service.
- Then, proceed with modeling the Clinical Service, the Patient Cohort, and the Service Line. The details about these concepts come from the QBP/Care Pathway.
- Then, enter in the Structure View the list of Units covered by the Service/Service Line.
- Then, fill the Organization View, with the Physician and Nursing organizations covering the above Units for the Service Line, and the eventual creation of new positions like the Service Line Director and Service Line Nursing Coordinator.
- In parallel with doing the above tasks, the Clinician would typically fill the Knowledge View, as they go with the modeling, and enter in text the list of Policies, Guidelines, Rules which govern the processes, services, units, and organization. Some would be hospital-specific.

- Then, the Clinician would decide on what specific functions in the Function View would be used to cover the Service/Service Line. Most of the time, they would keep all 7 functions by default.
- Then, the Clinician describes the events which would be required for the monitoring of the Service/Service Line. Typically, these would be high-level, clinical events about Patients, Services, Clinical Processes, Units, Functions which the Analysts would later on translate into lower-level events.
- The Clinician would not typically fill the Engineering View, because the Optimization/Simulation/MCDA tools would already have been used during the Strategic and Tactical decision-making process which led to the creation of the Service/Service Line. See section 5.3.5 and particularly Use Case 3 for more details.

As described in the following sections, the modeling can be done incrementally as new Services/Service Lines are created; the resulting COSS can be developed and built incrementally.

4.3.2 Example of COM Models

The Figure 4-12 below shows the COM Models for the Joint Replacement Service Line. They follow the Service Line Template in Figure 4-11 Service Line Template for COM Models, and are built using COMP and its MetaModel as described in Figure 4-6 COMP MetaModel Overview. The Views are identified by the blue dashed rectangles around them. The Service Line, Clinical Services, and Patient Cohorts are identified by the green dashed rectangle around them.

Not all Attributes, Operations, and Relationships are shown here in order to keep the figure readable.

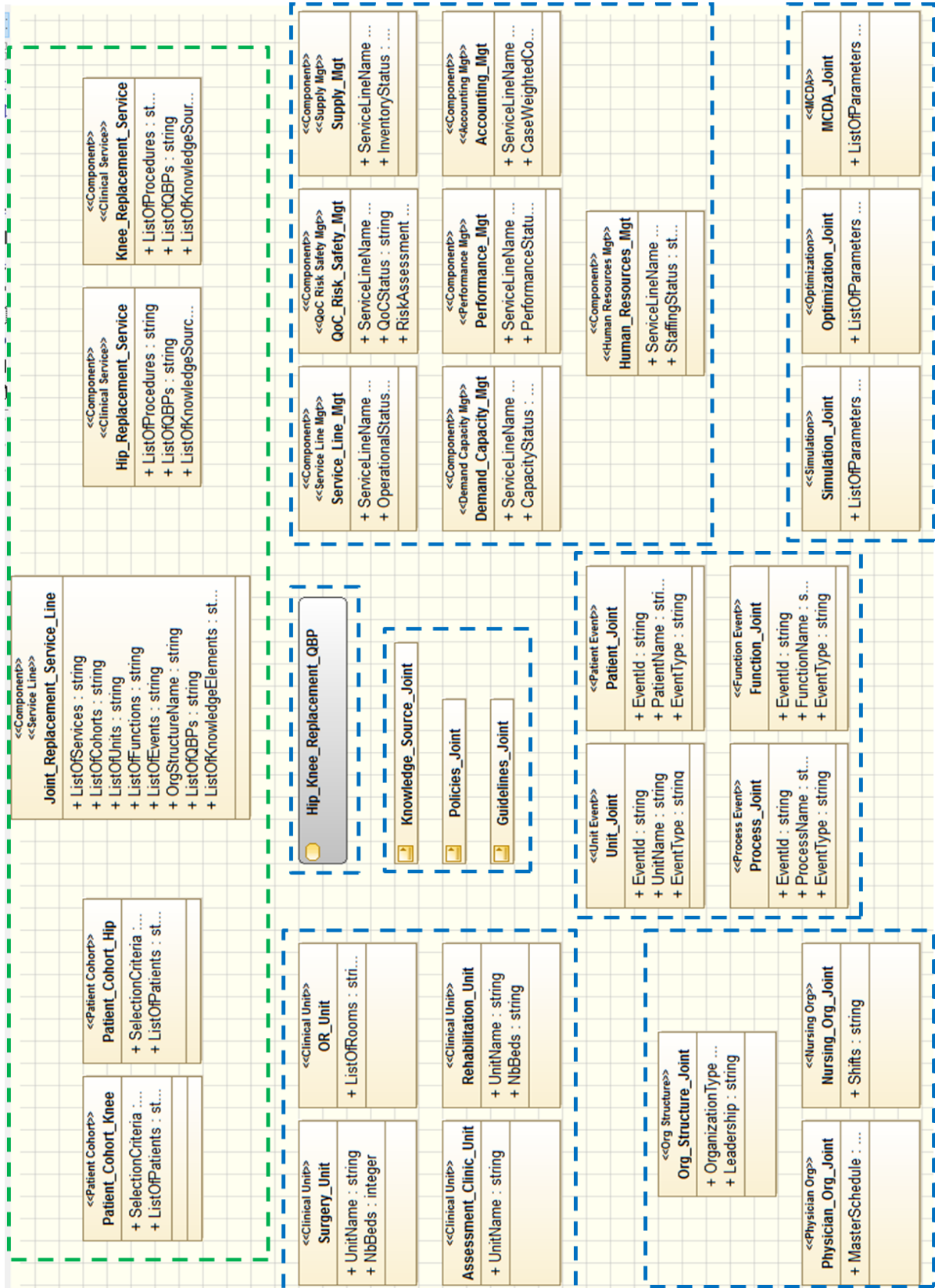


Figure 4-12 COM Models for Joint Replacement Service Line

4.3.3 Service Lines, Clinical Services, and Patient Cohorts

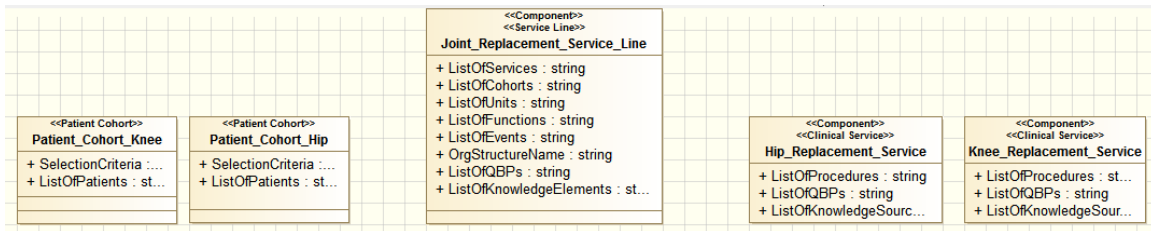


Figure 4-13 Service Lines, Clinical Services, and Patient Cohorts

The Joint Replacement service line is composed of the Hip Replacement clinical service and the Knee Replacement service. In reality, there are other orthopedic surgery services not shown in this example: Hip Fracture (which is an Emergency service, as opposed to an Elective one), Ankle and Knee surgeries, Spine surgery, etc. The Patient Cohorts are clearly identified groups of Patients meeting specific criteria for their inclusion in the cohort, to whom the clinical services are delivered, within the structure and organization of a service line which covers the entire patient journey throughout the entire hospital.

4.3.4 Function View

The Function View models the main management functions of the Service Line. It is derived from the columns of COM Functions Table.

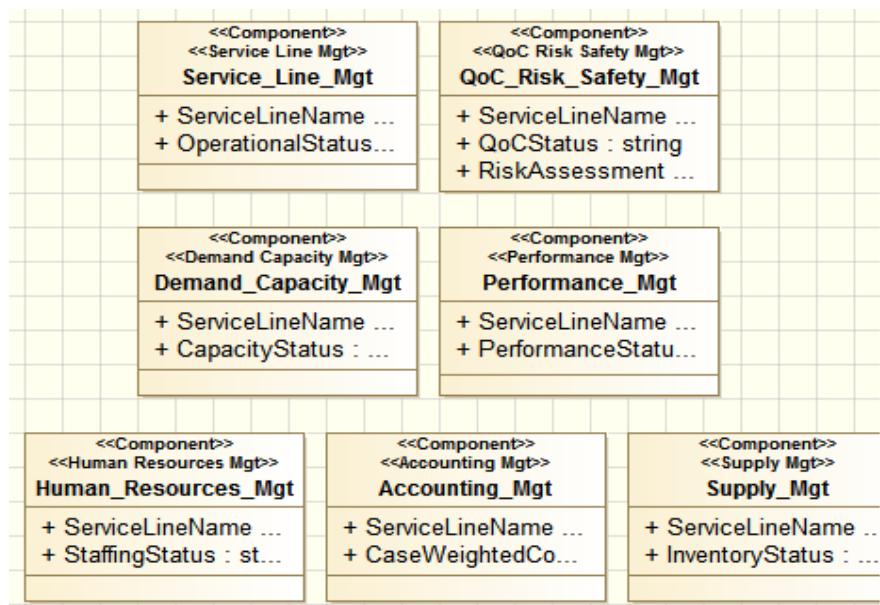


Figure 4-14 Function View

A function is modeled as a COMP class, stereotyped from a UML Component, with derived classes which can be customized for each hospital, as shown in the Table below.

Table 4-4 Function View

COM Models	
Views and Foundation Classes	Derived Classes
(Generic)	(for hospital XYZ)
Function View	
Service Line Mgt	Service Provisioning; Service Delivery; Service Monitoring
Demand & Capacity Mgt	Demand Smoothing; Demand Prediction; Capacity Scheduling; Capacity Allocation; Master Surgery Scheduling; End-to-end Patient Flow Mgt
Supply Mgt	Case Cart Mgt; Inventory management
Performance Mgt	Performance measurement; Event notifications; Real-time analysis; Historical analysis; Link Operational Performance and Financial Performance
QoC, Risk, & Safety Mgt	Clinical/Medical Performance; Adverse Event Management; Infection Control
Accounting Mgt	Service Line Reporting; Weighted Case Costing; Patient-level information and costing system
Human Resources Mgt	Absenteeism analysis; Real-Time staffing; Workforce Management; Training

The function contains generic knowledge; that is knowledge transferrable from one hospital to another. The customization for the hospital XYZ is typically done by subclassing and then customizing the data and relationships based on the hospital XYZ

policies, structure, organization, mandate, and type. The derived classes in Table 4-4 are guiding the Clinicians and Analysts in a structured and comprehensive approach to COM Modeling. The Functions go through a differentiated treatment during the SOAML Modeling; see section 4.4.1.

4.3.5 Structure View

The Structure View describes the hospital structure for COM, and more specifically the Service Line. It is a set of COMP classes, which are derived and then instantiated for a hospital. For instance, Hospital XYZ has a service line for Joint Replacement with 5 Operating Rooms, 2 Surgery Unit, 1 Rehabilitation Unit, and 1 Assessment Clinic.

Not all Units are shown in this example: Emergency Department, Medicine, etc.

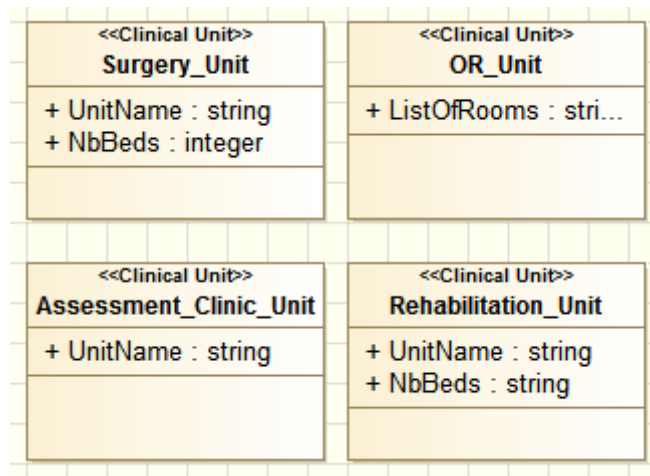


Figure 4-15 Structure View

Table 4-5 Structure View

COM Models	
Views and Foundation Classes	Derived Classes
(Generic)	(for hospital XYZ)
Joint Replacement Service Line	Hip Replacement Cohort Knee Replacement Cohort
Structure View	
OR	Hospital-specific derived classes
Surgery	Hospital-specific derived classes
Rehabilitation	Hospital-specific derived classes
Assessment Clinic	Hospital-specific derived classes

The Units are UML Classes containing:

- Rooms: single, double, triple, quad
- Isolation rooms
- Beds
- Equipment: ventilator, cardiac telemonitoring
- Supplies

Figure 4-16 below shows examples of patient journeys, for a given patient cohort. This route is a structure view, instead of a process view, because it simply describes the patient journey, not the clinical process he is on. The journeys in blue are managed by the Joint Replacement service line, and the ones in red are managed by the Cardiac Procedures service line.

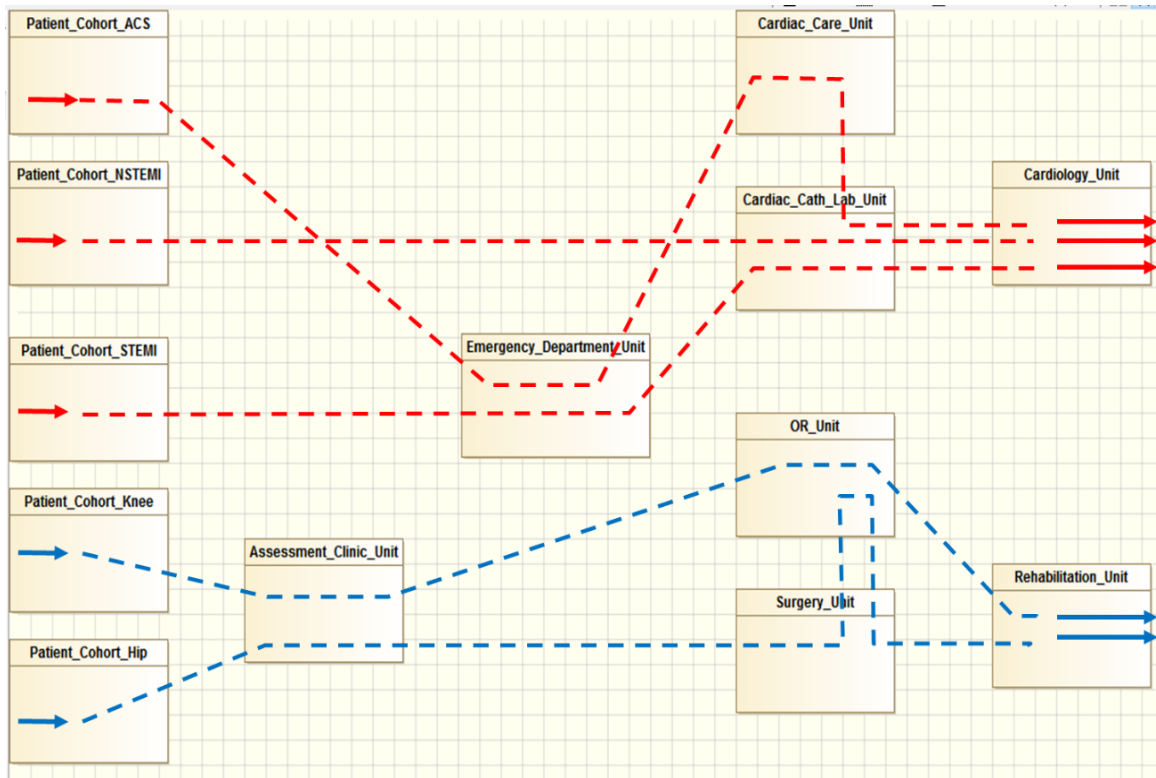


Figure 4-16 Patient Journeys through the hospital

The Structure View depends on other Views for the following:

- Knowledge View: the DMN rules enable reasoning on Structure view instantiated at run-time. An example is the rule set governing the interaction between some objects (clinical services, units, patients, and clinicians) for Continuity of Care when a patient is transferred from one unit to another.
- Event View: most Structure objects at run-time could produce events for notifications and/or alarms.
- Engineering View: it enables to size the Structure capacity; that is the number of objects (units, equipment, beds, etc) which will have to be instantiated at run-time.
- Process View: a process segment describes the sequence in which Structure objects would be used for a patient (see the example of Clinical Service Route above).
- Organization View: it describes the hospital organization as functional, divisional, or matrix; it also describes the model of care delivery. This impacts the roles and responsibilities of the staff and clinicians, which impacts the Structure capacity.

4.3.6 Process View

This is the central View of the COM Enterprise Architecture Diagram. The Process View describes the hospital care processes and Quality-Based Procedures. A large community hospital might have dozens of such processes. A university hospital might have 200 to 300 of such processes. The Joint Replacement Service line would have the Hip & Knee Replacement Quality-Based Procedure, the Admission and Discharge processes, and some other clinical and administrative processes common to most services.

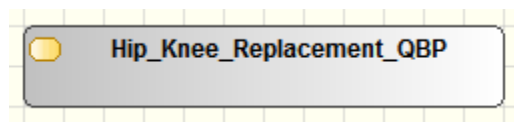


Figure 4-17 Process View

This view is represented by an Activity diagram describing the QBP using text and a copy of the QBP document. It is mapped into BPMN processes later in the development cycle (see section 4.4).

Table 4-6 Process View

COM Models	
Views and Foundation Classes	Derived Classes
(Generic)	(for hospital XYZ)
Joint Replacement Service Line	Hip Replacement Cohort Knee Replacement Cohort
Process View	
Hip & Knee Replacement QBP	Hospital-specific derived classes
Admission	Hospital-specific derived classes
Discharge	Hospital-specific derived classes

The Process View also supports the Structure View by, for instance, describing the flow of patients through units and the Clinical Service Routes.

The Process View has dependencies on all the other Views:

- Domain Knowledge: The process activities may require domain knowledge accessed as a Decision Support Service. Also, the process flow may be altered

based on decision outcomes made in the process Decision Nodes; these decisions are modeled with DMN rules and might contain domain knowledge.

- **Event View:** The processes may produce many different types of events, as defined by the BPMN standard (process start, end, cancel, etc). Other produced events could be process-specific (process input, output, run-time flexibility, exceptions, errors, etc). Finally, processes may consume events from other modules or information systems which may trigger a change in the process flow.
- **Structure View:** The processes Activities and Decision Nodes may access run-time objects (COOM instantiated from the Structure Views), as part of the blackboard architecture.
- **Engineering View:** it enables to size the process resources; that is the number of staff, clinicians, equipment, and other resources the process would need to properly execute.
- **Function View:** At run-time, the processes communicate with, and are coordinated by the Care Process Manager. They also communicate with other COSS modules, as described in the next section.
- **Organization View:** A value-based hospital is organized to handle care pathways and Quality-Based Procedures end-to-end; however, the hospital organization can still be functional (that is, vertical) or matrix (that is, both vertical and horizontal). This means that the customization of the Process Views will have to take the type of organization into account, and add or delete some process fragments.

4.3.7 Event View

Events are first-order entities in COM. They are modeled as COMP classes. They are mapped into Event UML models (describing the structure of events) and DMN models (describing the processing that the CEP engine has to do upon receiving or sending events)

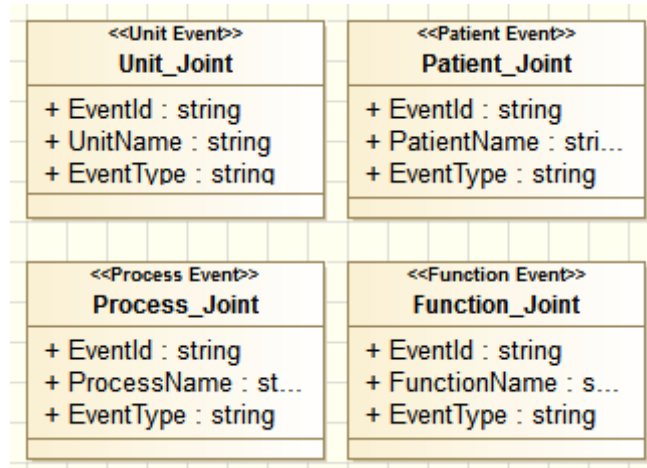


Figure 4-18 Event View

Table 4-7 Event View

COM Models	
Views and Foundation Classes	Derived Classes
(Generic)	(for hospital XYZ)
Joint Replacement Service Line	Hip Replacement Cohort Knee Replacement Cohort
Event View	
Patient Event	Hospital-specific; Service Line-specific
Process Event	Hospital-specific; Service Line-specific
Unit Event	Hospital-Specific; Service Line-specific
Function Event	Hospital-specific; Service Line-specific
Environment Event	Hospital-specific; Service Line-specific
Business Event	Hospital-specific; Service Line-specific

Here is a non-exhaustive list of Events:

- Admit/Discharge/Transfer events
 - Admission
 - Discharge
 - Transfer to another hospital

- Patient events
 - Patient move from one unit to another
 - Patient move from one bed to another
 - Patient put on care process
 - Patient taken out of care process
 - Patient move from one step of care to another
 - Wait times, of the patient, at 75% of breach target
 - Wait times breach (at 100% of target)
 - Surgical cancellation
- Process state events
 - Process-generated events: process instantiated, started, suspended, resumed, completed, aborted, terminated, broken, skipped
 - Process-consumed events: process activities change state upon receiving an event
- Unit events
 - No bed available
 - Bed ready, with type of bed
 - Bed occupancy at 90%
 - Bed occupancy at 100%
 - Use of Flex bed; Flex bed released
 - Use of Unfunded bed; Unfunded bed released
 - Full-Capacity Protocol activated in unit; Full-Capacity Protocol deactivated in unit
 - Stretcher in hallway; Stretcher released
- Process events:
 - Process start, end
 - Process flow change
 - Process exception
- Service Line Management events for each service instance
 - Co-morbidity: clinical service synchronized with another service
 - Activity XX not completed/confirmed

- Activity XX duration target breached
- Demand & Capacity Management events for each resource type
 - Resource YY not available
 - Resource YY available at hh:mm
 - Resource YY utilization breaching target
 - Staffing-to-Census Staff NN sent home; Staffing-to-Census Staff NN called
- Performance Management events for each performance indicator type
 - Indicator improving/degrading over last x hours
 - Indicator at 75% of breach threshold
 - Indicator at breach
- Supply Management events
 - Inventory of supply ZZ at 25%, Unit UU
 - Inventory of supply ZZ at 0, Unit UU
- QoC/Safety/Risk Management events
 - Adverse Event AE in Unit UU room xx
 - Isolation patient moved to room xx; Isolation patient left room xx
 - Escalation Event EE in Unit UU room xx
 - Code CC Event in Unit UU room xx
 - Hand Hygiene Event in Unit UU room xx
- Accounting Management events
 - Billable event start; Billable event end
 - Overtime start for Staff NN; overtime end for Staff NN
- HR Management events
 - Sick Time Staff NN
- COSS-specific Alarms (PFM): triggers from Units; triggers from Clinical Services; triggers from Resources; triggers from Demand Management; triggers from Capacity Management; triggers from Real-Time Demand Capacity; triggers from Infection Control (isolation rooms)
- Environment events:
 - Patient location

- Physician location
- Equipment tracking
- Diagnostic Imaging/Lab results available
- Infrastructure events:
 - Equipment down; equipment up
 - IS down; IS up
- Knowledge events: clinical and business events produced and/or consumed by blackboard Knowledge Sources
- Organization events:
 - Real-time staffing events
 - Sick-time tracking events
 - Staffing-to-Census events

The Event View is structured in layers, mapping the TOGAF Enterprise Architecture layering:

- Business
- Service
- Infrastructure, Environment

The Event View has dependencies on 2 COM Views:

- Knowledge View: these are the Knowledge Sources for the blackboard
- Structure View: instantiated into the blackboard on which the Knowledge Sources reason

4.3.8 Knowledge View

The Knowledge View describes the formal and informal knowledge used in the hospital Service line. It is made actionable as a set of Knowledge Sources used by the COSS blackboard. The knowledge comes from guidelines, policies, care pathways, etc.

The Knowledge View is modeled as COMP InformationItem. They map into DMN Rule sets which, at run-time, are used in Knowledge Sources. The Knowledge View provides support to most of the other COMP Views.

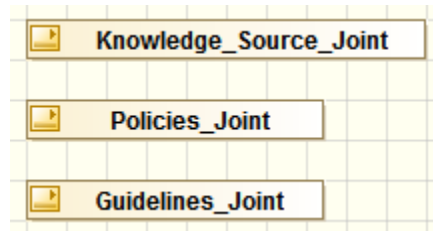


Figure 4-19 Knowledge View

Table 4-8 Knowledge View

COM Models	
Views and Foundation Classes	Derived Classes
(Generic)	(for hospital XYZ)
Joint Replacement Service Line	Hip Replacement Cohort Knee Replacement Cohort
Knowledge View	
Knowledge Sources (used in COSS BlackBoard)	Knowledge Source for Demand & Capacity Mgt
	Knowledge Source for Operational Performance Management
	Knowledge Source for Quality Performance Management
	Knowledge Source for Financial Performance Management
Policies	Full-Capacity Escalation; Surgery Cancellation
Guidelines	Clinical Guidelines

Here are examples of Knowledge View for the Decision Support Services provided in the COSS for the Hip & Knee Replacement Service Line:

- the Demand Management DSS is in charge of smoothing the elective patient demand and managing the emergency patient demand. Its Knowledge Model describes the rule sets for booking elective surgery procedures such as to optimize the OR utilization and the Surgery ward bed occupancy, while meeting the constraints of the Surgeon schedule and the hospital objective on wait times. The rule sets depend on the use of Optimization tools.
- the Capacity Management DSS is in charge of optimizing the capacity allocation in order to anticipate the predicted demand and meet the actual demand. Its Knowledge Model describes the rule sets for the allocation of resources, scheduling of Physicians, staffing of Nurses, and allocation of Ancillary Services. The rule sets depend upon Simulation tools.
- the Full-Capacity Protocol DSS is in charge of managing in real-time a surge situation when the hospital activates the Full-Capacity Protocol. This complex DSS and its Knowledge Model are further detailed in Section 4.6.8.

The Knowledge View has dependencies on 3 Views:

- Structure View: instantiated into the COOM blackboard upon which the Knowledge Sources do the reasoning
- Event View: Knowledge View describes production and/or consumption of events as part of their reasoning
- Engineering View: at run-time, the Knowledge Sources of the blackboard rely on Optimization tools, Simulation tools and Multi-Criteria Decision Analysis tools as part of their reasoning.

Here are other types of knowledge rules for the Joint Replacement Service Line:

- Joint Assessment: Coordinated intake assessment; Preparation for Surgery; Pre-Admission Screening
- Surgical scheduling and booking of joint replacement cases, in order to balance elective and emergency orthopaedic surgeries
- Scheduling of Surgeons and Anesthetists

- Scheduling and Staffing of Peri-Op Nurses
- Supply management of joint implants
- Procedure cancellation in case of Full-Capacity Protocol activation
- Surgery ward bed allocation, in order to balance elective and emergency cases
- Homecare Rehab

4.3.9 Organization View

The Organization View is modeled as a set of COMP classes.

The Service Line organization type is fairly recent in hospitals [SLM NHS UK]. It introduces a matrixed organization in a hospital traditionally organized along vertical silos. This requires a redefinition of reporting lines, roles and responsibilities, and also a redefinition of decision-making rights. Typically, a new role of Service Line Director will be created, reporting to the Senior Executive Team, and staff would now report to both the new Service Line Director and to their Clinical Director as traditionally. The organization is hospital-specific, and can be service line-specific because two service lines may decide on different roles & responsibilities.

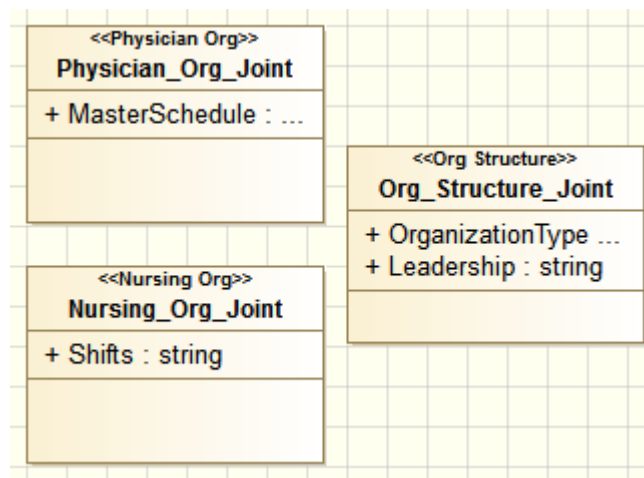


Figure 4-20 Organization View

Table 4-9 Organization View

COM Models	
Views and Foundation Classes	Derived Classes
(Generic)	(for hospital XYZ)
Joint Replacement Service Line	Hip Replacement Cohort Knee Replacement Cohort
Organization View	
Organization Structure	Matrix organization; Service line structure; Leadership roles; Decision rights at each level
Physician Organization	Roles & Responsibilities; New role of Joint Replacement Medical Director
Nursing Organization	Roles & Responsibilities; New role of Joint Replacement Nursing Coordinator

The Organization View includes:

- Hospital organization structure: Functional (by units and specialties), Divisional (by groups of patients/procedures), or Matrix (a hybrid of the previous two). A transformation to value-based hospital means a move from a Functional Organization to either a Divisional Organization (tertiary hospitals are already organized this way) or a Matrix Organization (this could be a preferred intermediate step or even the final step for many community hospitals).
- Hospital organizational policies (in Knowledge Sources): policies for real-time staffing when facing absenteeism; nurse-patient ratios; staffing skill mix (Registered Nurse versus Registered Practical Nurse)
- Physician organization: Scheduling policies, On-call policies, Rounding (Geographic assignment)
- Nursing organization: Model of nursing clinical practice, Direct care delivery, Resource allocation policies (staffing-to-census), Managerial Support, Shift and Staffing Policies, Allied Health support

- Physician-Nursing Collaboration: Physician-Nurse teams in ED, Multi-disciplinary Rounding in Medicine

Besides providing support to the HR Management function, the Organization Views also provide support to the Process Views and Structure Views as described above.

The Organization View has dependencies on 3 Views:

- Structure View: the Organization View reasons about the Structure View when it is instantiated into COOM at run-time; for instance, to optimize and smoothe the real-time staffing of Nurses across several units in the hospital.
- Event View: The Organization View produces and/or consumes events for the real-time staffing of Nurses and Ancillary Services and to support Staffing-to-Census.
- Knowledge View: it provides the DMN rules sets used in the Organizational View to reason about the implications of a Matrix organization on the roles & responsibilities of Clinicians, and on the required communications within the Care Teams and with the rest of the hospital.

4.3.10 Engineering View

The Engineering View is modeled as a set of COMP classes describing the service interfaces to the Optimization, Simulation, and Multi-Criteria Decision Analysis tools.

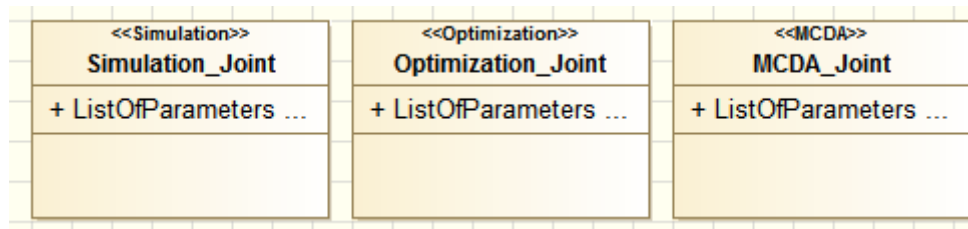


Figure 4-21 Engineering View

Table 4-10 Engineering View

COM Models	
Views and Foundation Classes	Derived Classes
(Generic)	(for hospital XYZ)
Joint Replacement Service Line	Hip Replacement Cohort Knee Replacement Cohort
Engineering View	
Optimization	Service Line design; Clinical Service Design optimization; OR Capacity Optimization; Master Surgery Schedule Optimization
Simulation	Service Line simulation; Patient Flow Simulation; Clinical Service Simulation
Multi-Criteria Decision Analysis	Real-time decision support

The Engineering Tools used in COM include

- Linear Programming for Optimization: Master Surgery Scheduling, smoothing of bed occupancy in the units, staffing and scheduling Nursing shifts, etc.
- Discrete Event Simulation: dimensioning of resource allocation to the units, prediction of patient demand, simulating the impact of a Full-Capacity Protocol at run-time.
- Multi-Criteria Decision Analysis: used in the Full-Capacity Protocol DSS in order to decide among several alternative Actions based on their impact on patient flow, patient satisfaction, staff satisfaction, finances, and performance indicators.

The Engineering View provides support to the Process, Structure, Function, and Knowledge Views.

4.4 UML/BPMN/DMN Models

The Model Transformation from COM Models to UML/BPMN/DMN Models is taking place in several manual steps, described below.

4.4.1 SOAML Modeling

Following the SOAML methodology (section 2.5.6), the modeling steps are the following to define the services (SOAML Participants) that are available in the hospital Service Oriented Architecture (SOA):

- Identification of SOAML Participants, based on domain analysis. This has been done, and should not need to be re-done again. A list of 14 Participants has been finalized and described below.
- Mapping the COM Models into the 14 SOAML Participants, as described in Figure 4-22 Overview of Mapping from COM Models to SOAML Participants below.
 - List of the 14 SOAML Participants (with their UML Components), in Figure 4-23 SOAML Participants and UML Components. The set of UML Components composing each Participant comes as a group: if the Participant is required, based on the COM Models and Mapping, then all its UML Components are required.
 - The Mapping is described in Figure 4-24 Mapping from COM Models to SOAML Participants. This is done manually each time COM Models are created. The goal of the Mapping is simply to identify the Participants required, based on the COM Models, and hence the list of UML Components required, which directly impacts the COSS architecture.
 - The Service Line and Clinical Service are mapped into the Service Line Manager Participant. This Participant is required all the time.
 - The Patient Cohort is mapped into both the Service Line Manager and Patient Flow Manager Participants. The Patient Flow Manager is required all the time.
 - Structure View is mapped into the Service Line Manager Participant.
 - Functions in the Function View are mapped to different Participants as shown. It has to be noted that 3 Functions are mapped into 2 Participants, and the others into 1 Participant.
 - Process View is mapped into the Patient Flow Manager and Process Manager Participants. They are required all the time.

- Organization View and the Human_Resources_Mgt Function are both mapped into the Human Resources Manager Participant.
 - Event View is mapped into the Event Manager Participant. The Event Manager is required all the time.
 - Knowledge View is mapped into the Rules Manager Participant. The Rules Manager is required all the time.
 - Engineering View is mapped into the Engineering Tools Manager Participant.
 - The Hospital Map Manager and Blackboard Manager Participants are not involved in the Mapping because they are IS concepts rather than clinical ones.
- Identification of SOA services between the Participants in Figure 4-25 Overview of SOA Services between SOAML Participants. Analysts can edit these services, knowing that this has a direct impact on the UML Components composing the Participants and the services between them (see below). Just like Service/Request Interfaces are used to model communications between Participants, Service/Request Ports are used to model communications between Components. This is described in the OMG SOAML v1.0.1 specification [OMG].
 - Figure 4-26 Example of Service Line Manager Participant with Service/Request Interfaces (blue), and Components with their Service/Request Ports (yellow).
- List of UML Components composing the Participants. This list has been done once by us. However, in rare cases where necessary, Analysts with the appropriate training could modify the Component list, knowing that this has a direct impact on the COSS architecture.
 - Figure 4-27 Examples of Services between UML Components composing Service Line Manager Participant: shown with their Service/Request ports.
- Identification of SOA services between Components. This has been done once by us. However, in rare cases where necessary, Analysts with the appropriate training could modify these services, knowing that this has a direct impact on the COSS architecture.

- Figure 4-28 List of 14 SOAML Participants with Service/Request interfaces (blue), and their 39 UML Components (yellow)

The purpose of Figure 4-22 is just to give a sense of the mapping on a single view. A more readable version is in Figures 4-23 and 4-24.

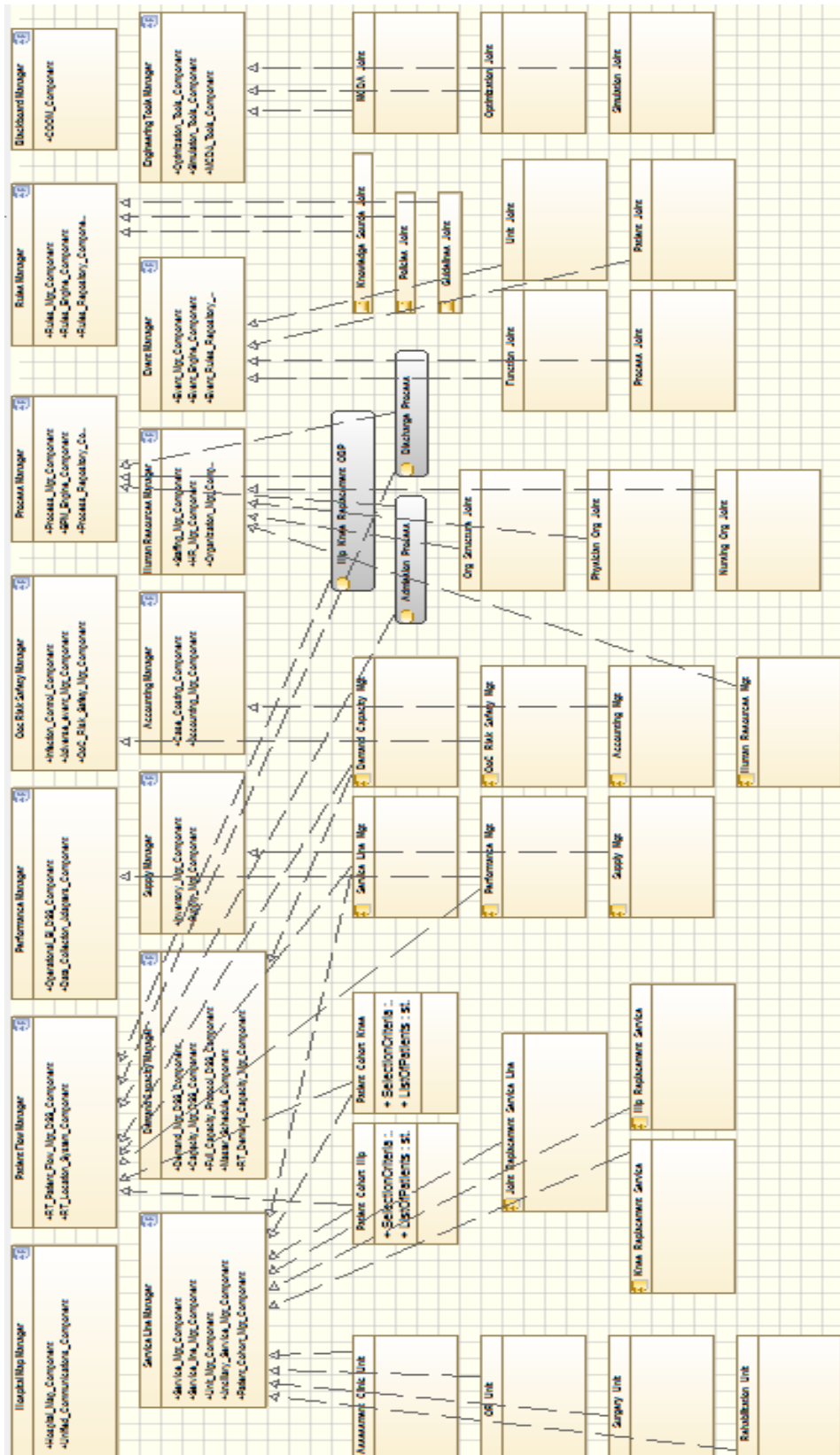


Figure 4-22 Overview of Mapping from COM Models to SOAML Participants

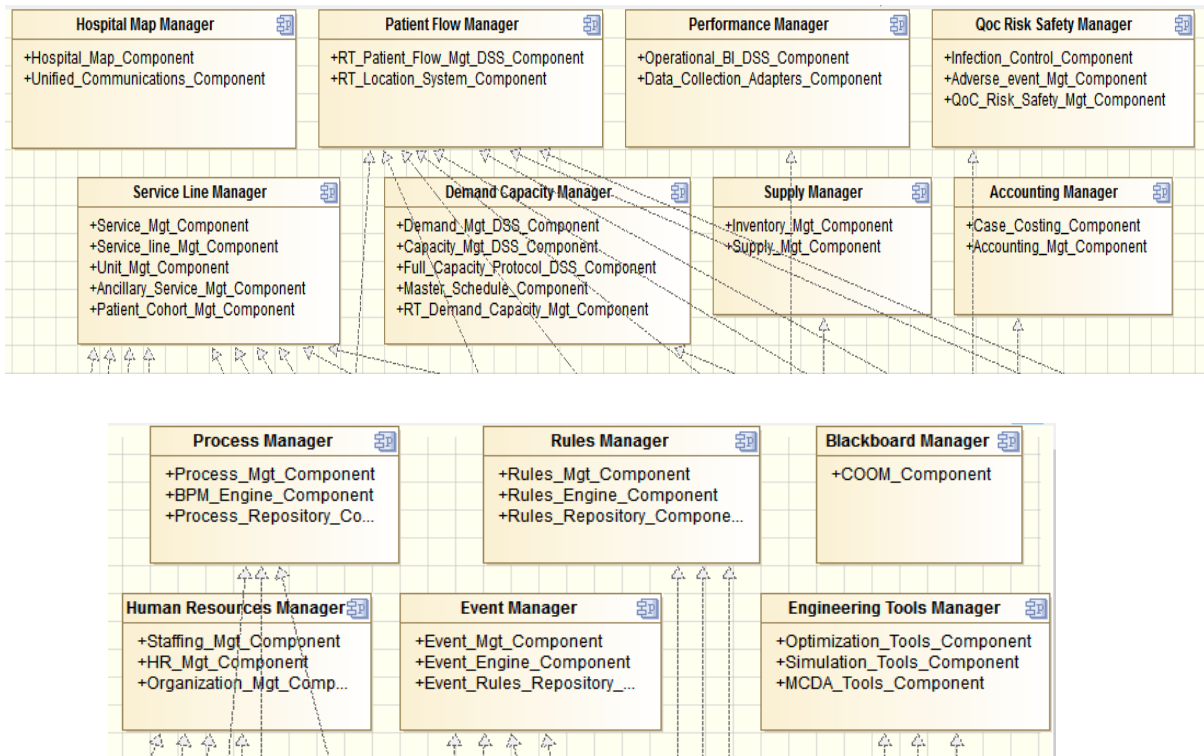


Figure 4-23 SOAML Participants and UML Components

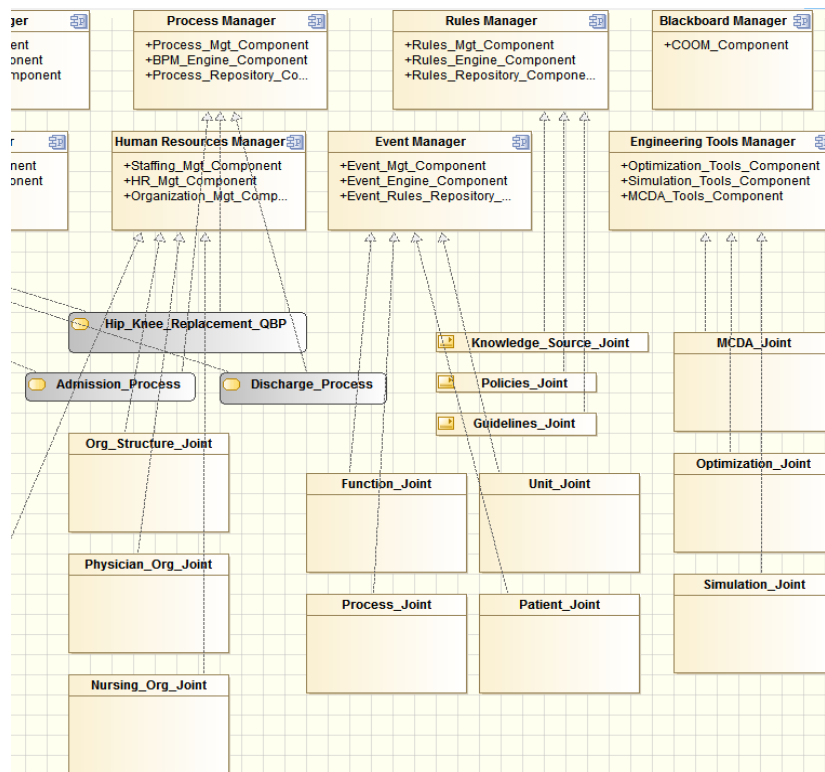
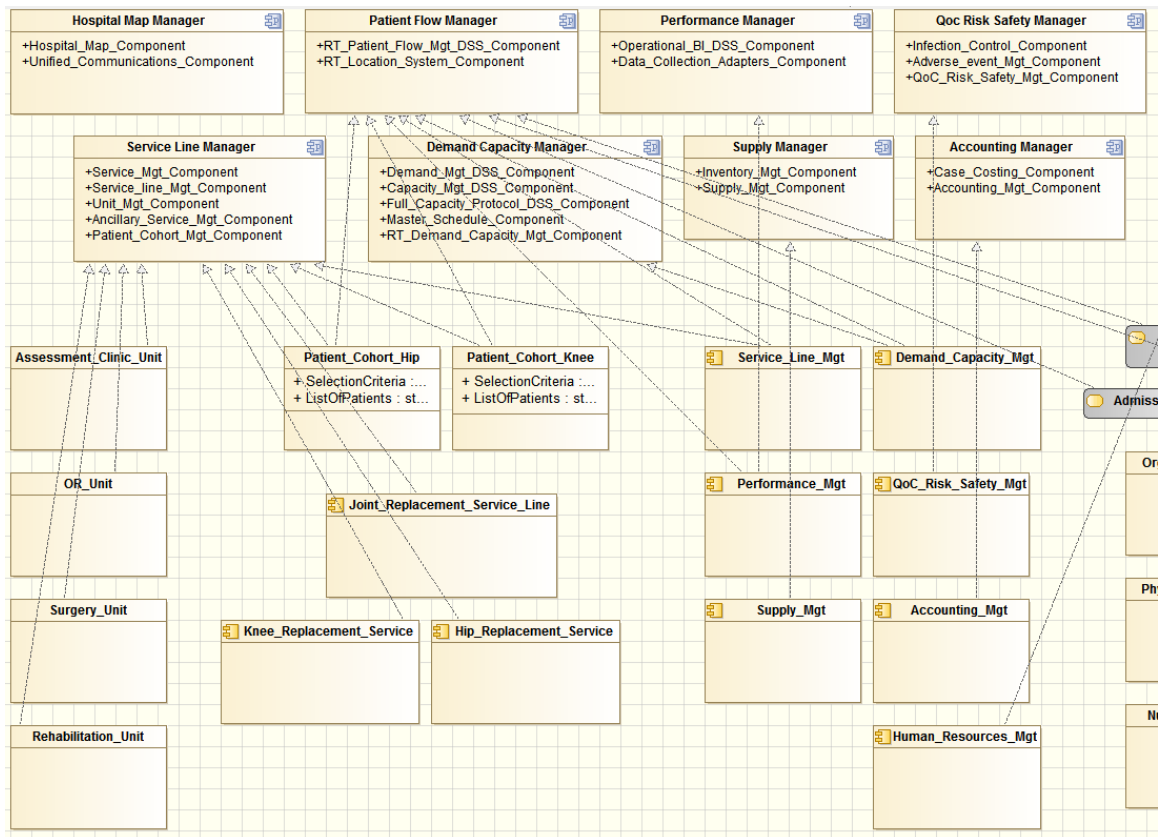


Figure 4-24 Mapping from COM Models to SOAML Participants

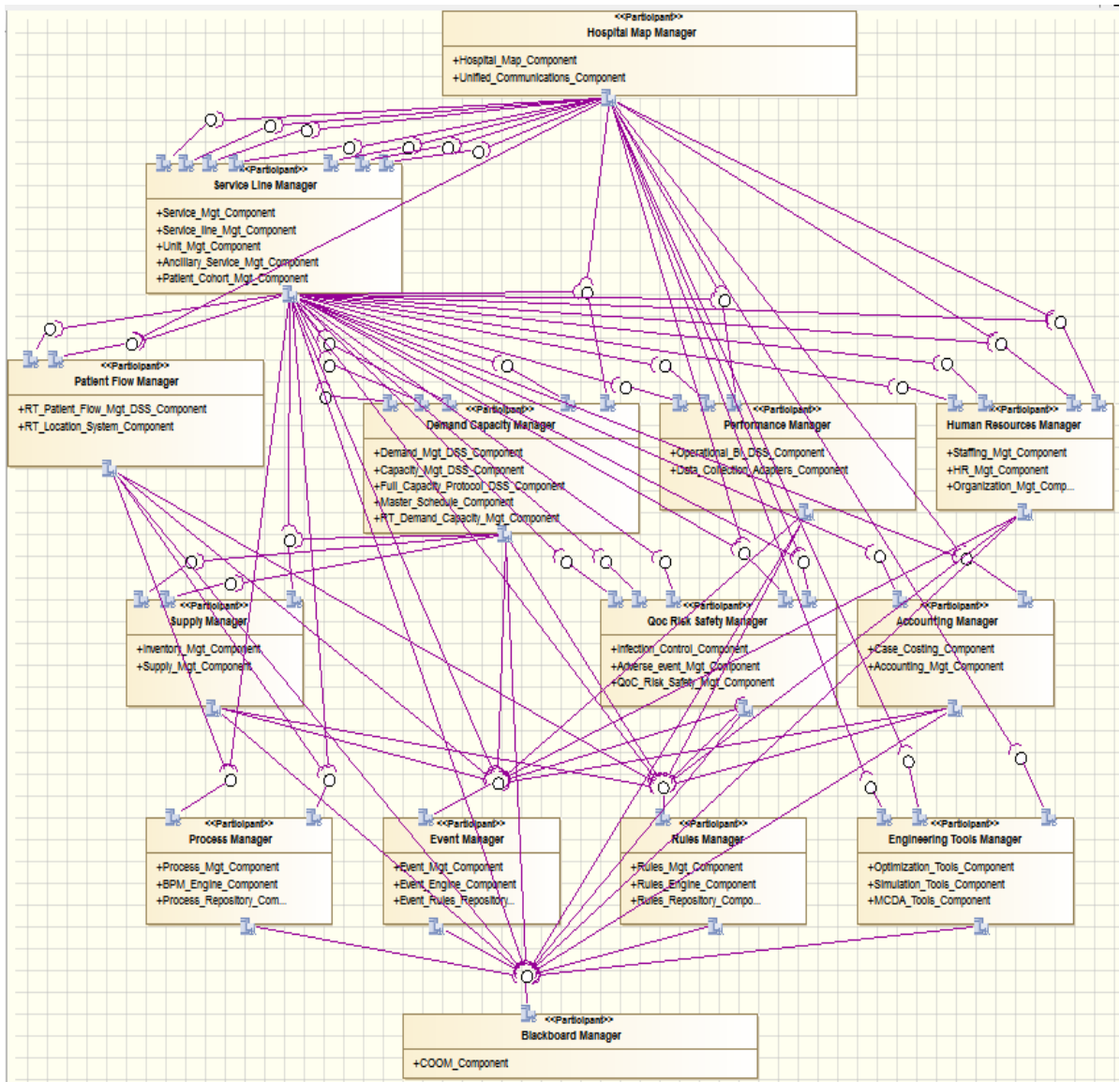


Figure 4-25 Overview of SOA Services between SOAML Participants

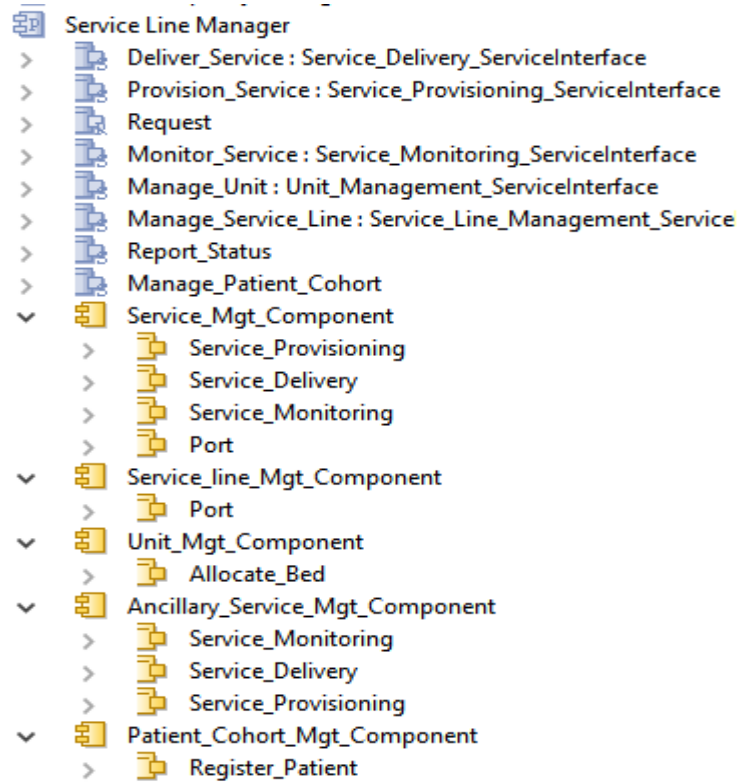


Figure 4-26 Example of Service Line Manager Participant with Service/Request Interfaces (blue), and Components with their Service/Request Ports (yellow)

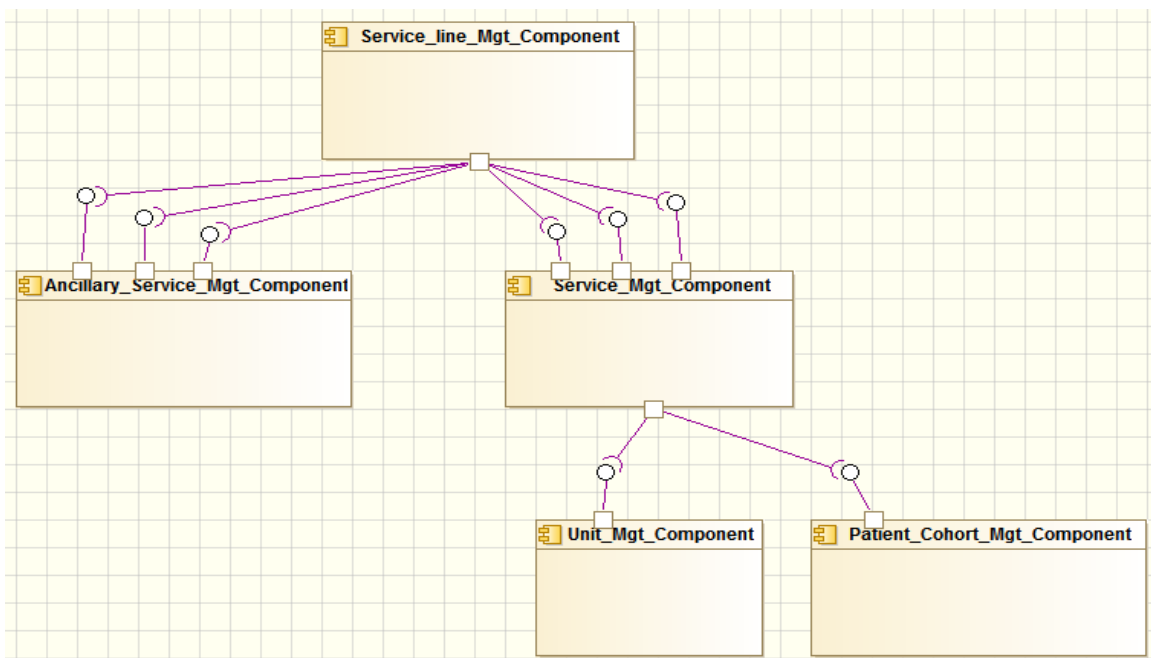
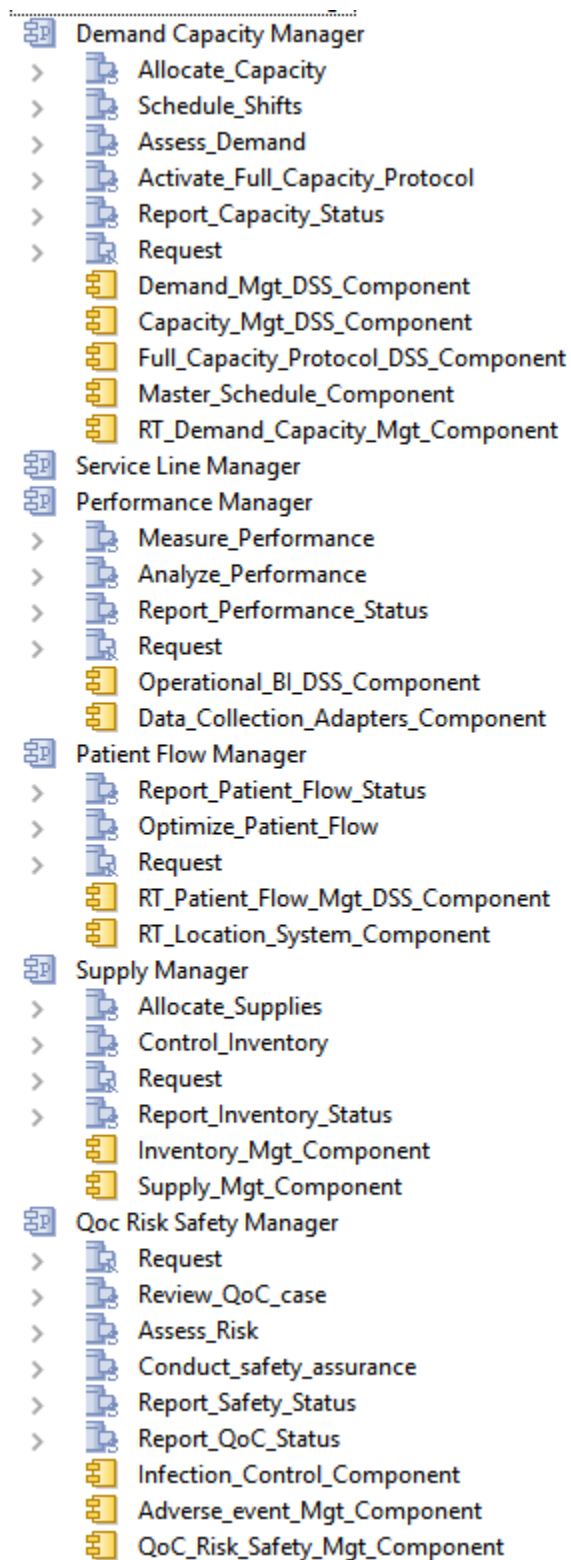


Figure 4-27 Examples of Services between UML Components composing Service Line Manager Participant



- Accounting Manager
 - > Compute_case_cost
 - > Report_Case_Costing_Status
 - > Request
 - Case_Costing_Component
 - Accounting_Mgt_Component
- Human Resources Manager
 - > Manage_Workforce
 - > Activate_Staffing_to_Census
 - > Report_HR_Status
 - > Request
 - > Update_Organization
 - Staffing_Mgt_Component
 - HR_Mgt_Component
 - Organization_Mgt_Component
- Process Manager
 - > Execute_QBP
 - > Execute_Process
 - > Request
 - Process_Mgt_Component
 - BPM_Engine_Component
 - Process_Repository_Component
- Event Manager
 - > Process_Event
 - > Request
 - Event_Mgt_Component
 - Event_Engine_Component
 - Event_Rules_Repository_Component
- Rules Manager
 - > Execute_Rules
 - > Request
 - Rules_Mgt_Component
 - Rules_Engine_Component
 - Rules_Repository_Component
- Engineering Tools Manager
 - > Execute_Optimization
 - > Execute_Simulation
 - > Execute_MCDA
 - > Request
 - Optimization_Tools_Component
 - Simulation_Tools_Component
 - MCDA_Tools_Component

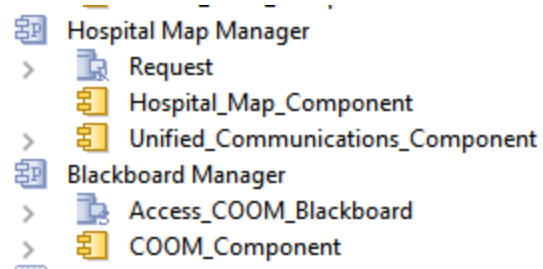


Figure 4-28 List of 14 SOAML Participants with Service/Request interfaces (blue), and their 39 UML Components (yellow)

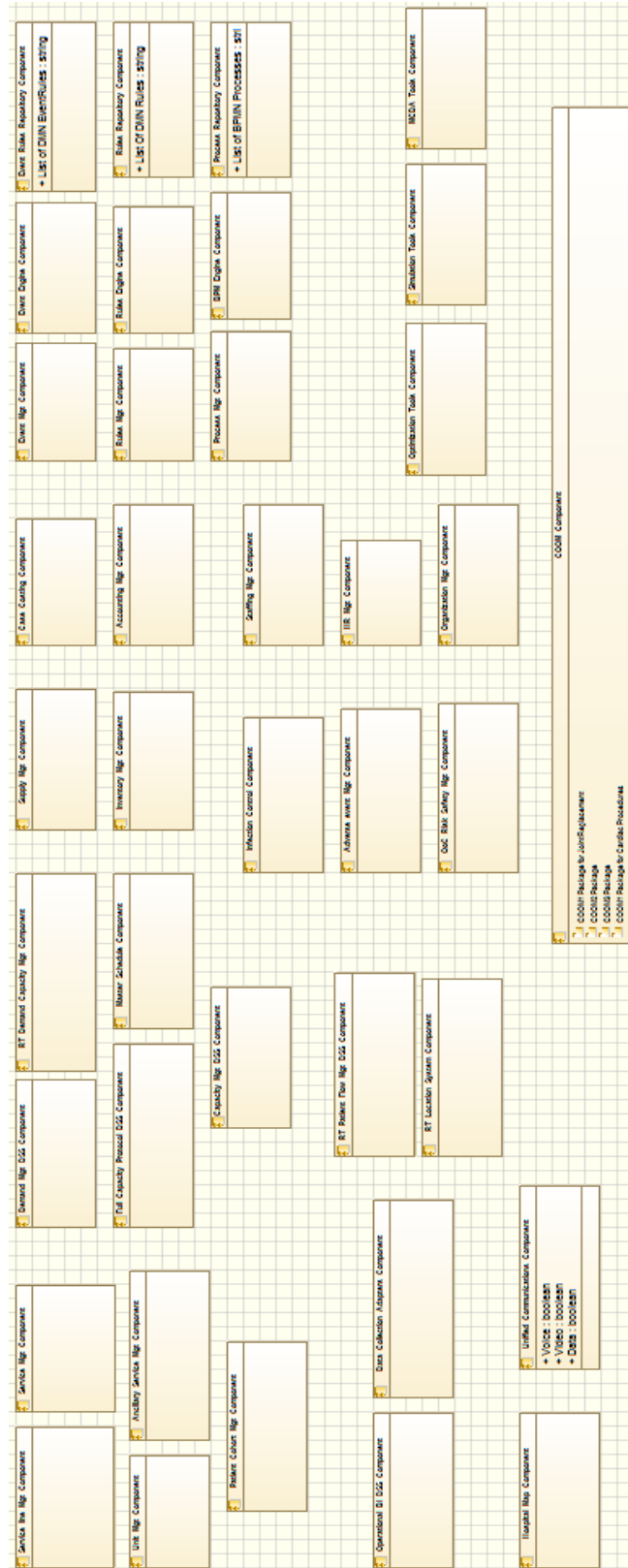


Figure 4-29 Overview of 39 UML Components

The outcome of these manual transformation steps is a list of 39 UML Components, in Figure 4-29 Overview of 39 UML Components, which are used by COSBench for a 1-to-1 transformation into COSS Modules, as described in section 4.5.

Typically, for most Clinical Services and/or Service Lines, the UML/BPMN/DMN modeling done by Analysts is focused on the following areas:

- COOM modeling, with COOM1 containing the Blackboard information model, is described in Section 4.4.2
- BPMN modeling, producing process models contained in the Process Repository, are described in section 4.4.3
- DMN modeling, producing event and knowledge rules contained respectively in the Event Rules Repository and the Rules Repository, are described in section 4.4.4

4.4.2 COOM Modeling

The above UML Components are used to generate COSS Modules. Some of these modules work together in a Blackboard Architecture Pattern, and need to share data and knowledge. This is done via the Clinical Operations Object Model (COOM) which is the blackboard structure.

COOM is a set of run-time objects used in the COSS blackboard as part of Model-Based Reasoning. They are designed in layers, following the COM Functions Table rows. The COOM blackboard is composed of 3 interoperating blackboards, COOM1/2/3, per Figure 4-30 below:

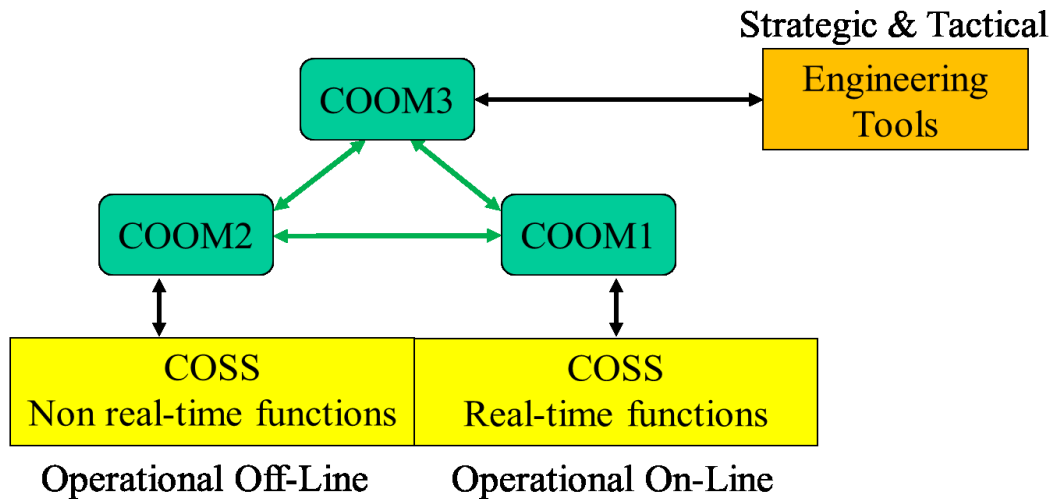


Figure 4-30 COOM Blackboard structure

The COOM3 blackboard is used by the Engineering Tools

(Optimization/Simulation/MCDA) for Strategic and Tactical decision-making:

- Strategic Level: high-level-granularity objects supporting strategic decisions; objects generate inputs for Optimization/Simulation/MCDA tools. Hospital, Units, Policies, case mix, patient mix, service mix. High-level service models for patient groups.
- Tactical Level: mid-level-granularity objects supporting tactical decisions; objects generate inputs for Optimization/Simulation tools. Units, Beds, Processes, Organization, Groups of Patients, Groups of Nurses, Groups of Physicians. Detailed service models for patient groups.

Figure 4-31 shows the COOM3 Package, and the main types of information used by the Engineering Tools.

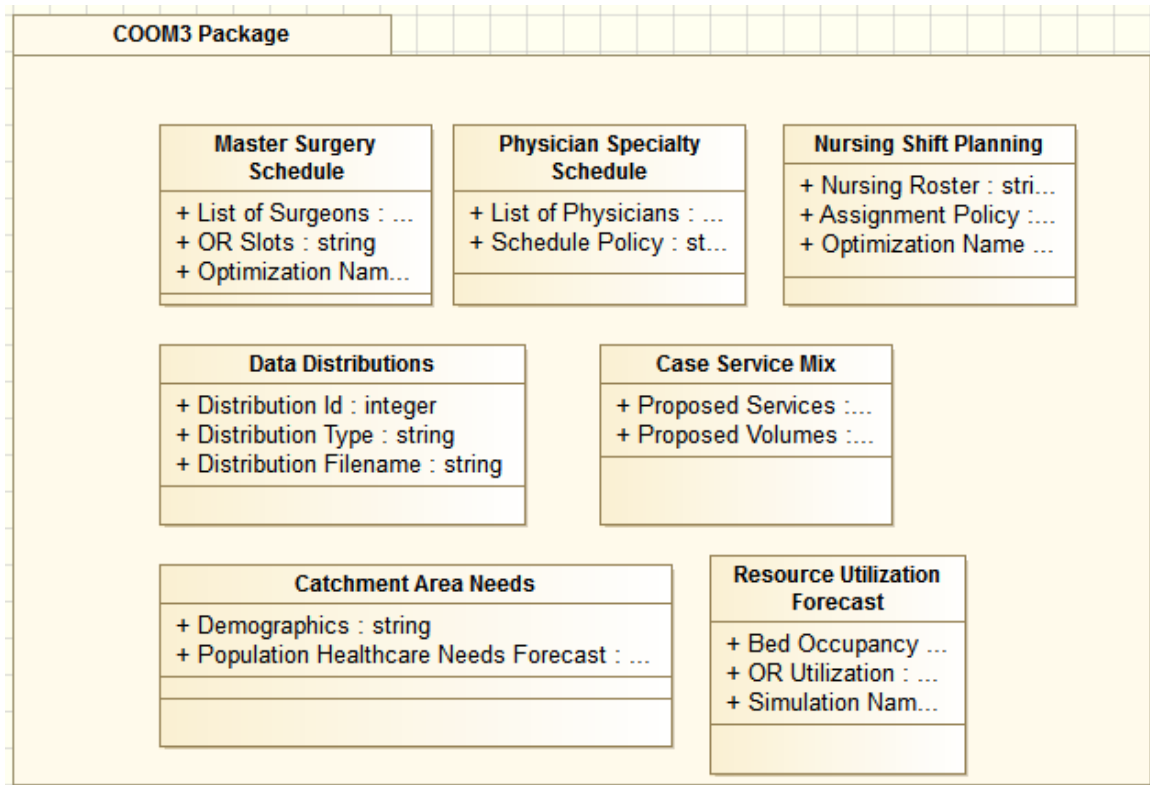


Figure 4-31 COOM3 Package

The COOM2 blackboard is used by some COSS Modules for short-term planning, at the Operational Off-line decision-making level (these COSS Modules are described in section 4.6):

- Demand Management DSS
- Capacity Management DSS
- Operational Business Intelligence DSS
- Service Line Management
- Staffing Management

Figure 4-32 shows the COOM2 Package, and the main types of information used.

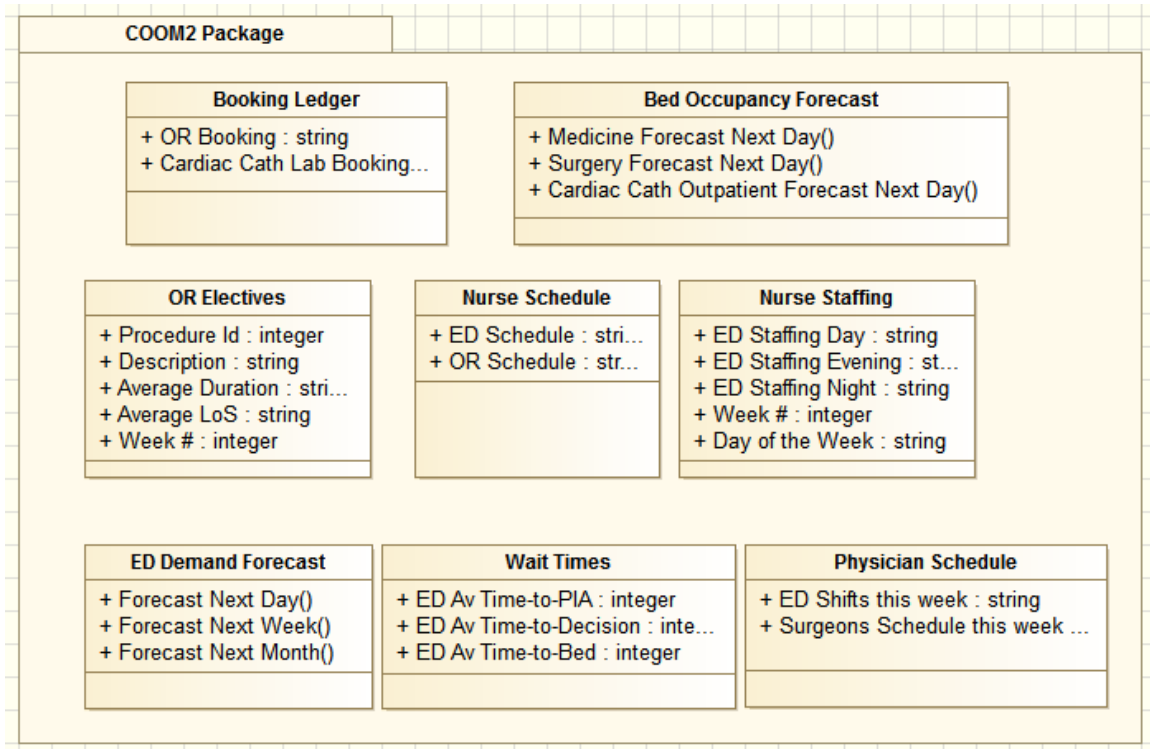


Figure 4-32 COOM2 Package

The COOM1 blackboard is used by the COSS in (near) real-time, at the Operational On-line level of decision-making. It is composed of low-level-granularity objects supporting real-time operations at point-of-care:

- Units, Beds, individual Patients, individual Nurses, individual Physicians.
- Flow objects (patients, work, supplies, information).
- Care Plans for individual patients.
- Events

As opposed to COOM3 and COOM2 which are fairly generic and are mostly independent of the service line being supported, the COOM1 information model varies from one service line to another. At run-time, the COOM1 blackboard contains object instances for all the service lines being supported by the COSS.

Figure 4-33 below shows an example of COOM1 for the Joint Replacement service line:

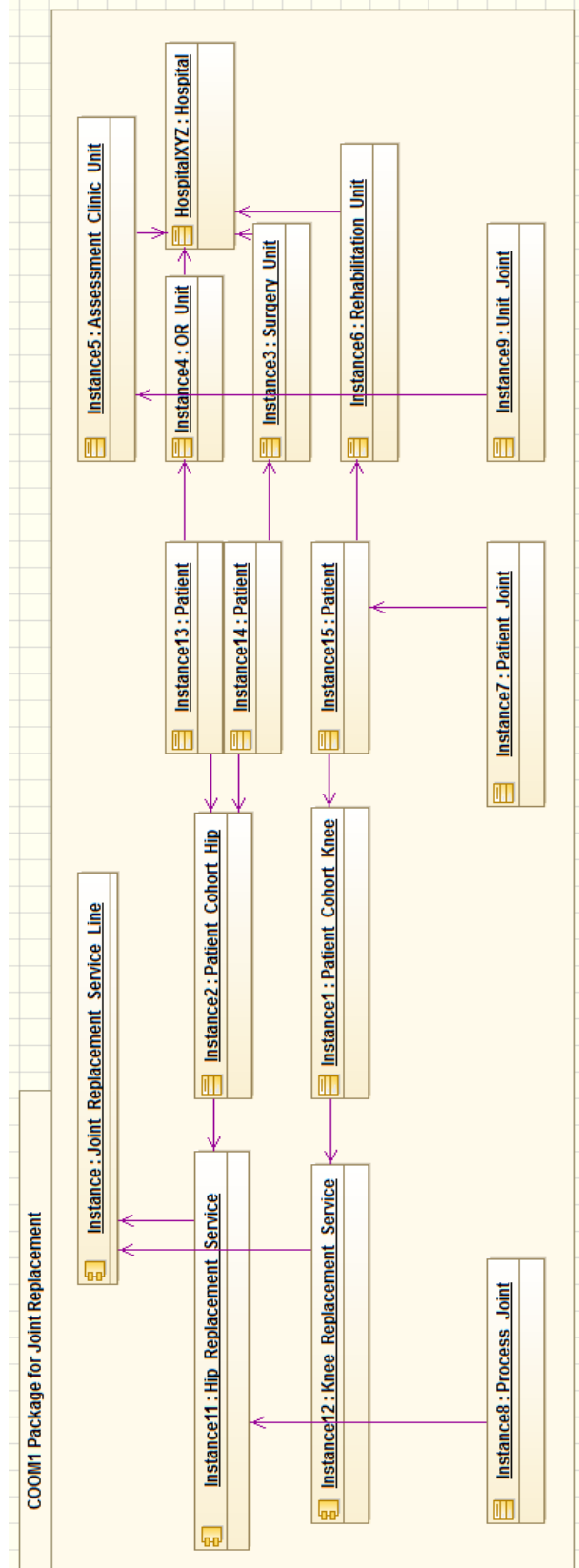


Figure 4-33 Example of COOM1 for Joint Replacement

4.4.3 BPMN Modeling

Next, the BPMN processes are designed. They are stored in the Process Repository Component, are managed by the Process Management Component, and are executed by the BPM Engine Component.

The clinical process modeling is central to COM modeling and to UML/BPMN/DMN modeling because the QBP/Care Pathways completely drive the rest of the modeling. Clinicians put as much details in text format as possible in the Process View, and Analysts derive the UML/BPMN/DMN models accordingly, starting with BPMN process models.

Figure 4-34 shows an example of a BPMN Process for the Hip & Knee Replacement QBP. The patient is referred by their Primary Care Physician to a Central Intake Assessment center who, based on wait times and patient preferences, allocates the Orthopedic Surgeon. Following the consultation, if the decision is indeed to operate, the patient is referred to a Clinic where the preparation for surgery is made. On the day of surgery, the patient is screened, admitted, and undergoes pre-operative preparation. Following the surgery, the patient is transferred to the Surgery Unit, and is normally discharged 2 or 3 days later with order for physiotherapy at a Rehab Clinic.

In this example, the wait activities are made explicit because the wait times are first-order entities, and are reported to the MOHLTC as part of the monthly/quarterly performance reporting.

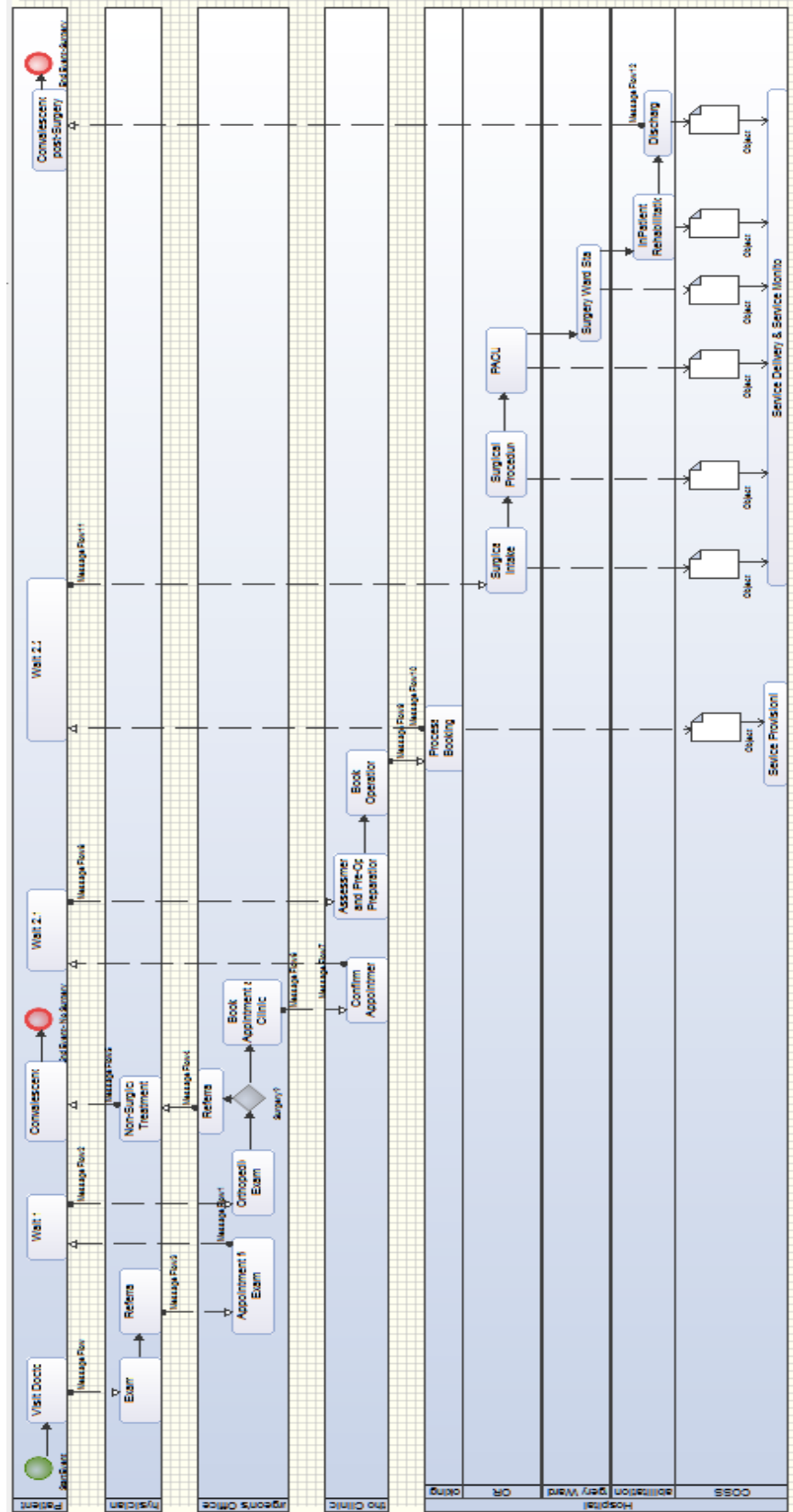


Figure 4-34 BPMN Process for Hip & Knee Replacement QBP

4.4.4 DMN Modeling

After the BPMN model, the Event Rules and knowledge Rules are designed. Here are examples in pseudo-code; the actual rules are built using DMN.

The Event Rules are stored in the Event Rules Repository Component, are managed by the Event Management Component, and are executed by the Event Engine Component. Figure 4-35 gives an example of Event Rules:

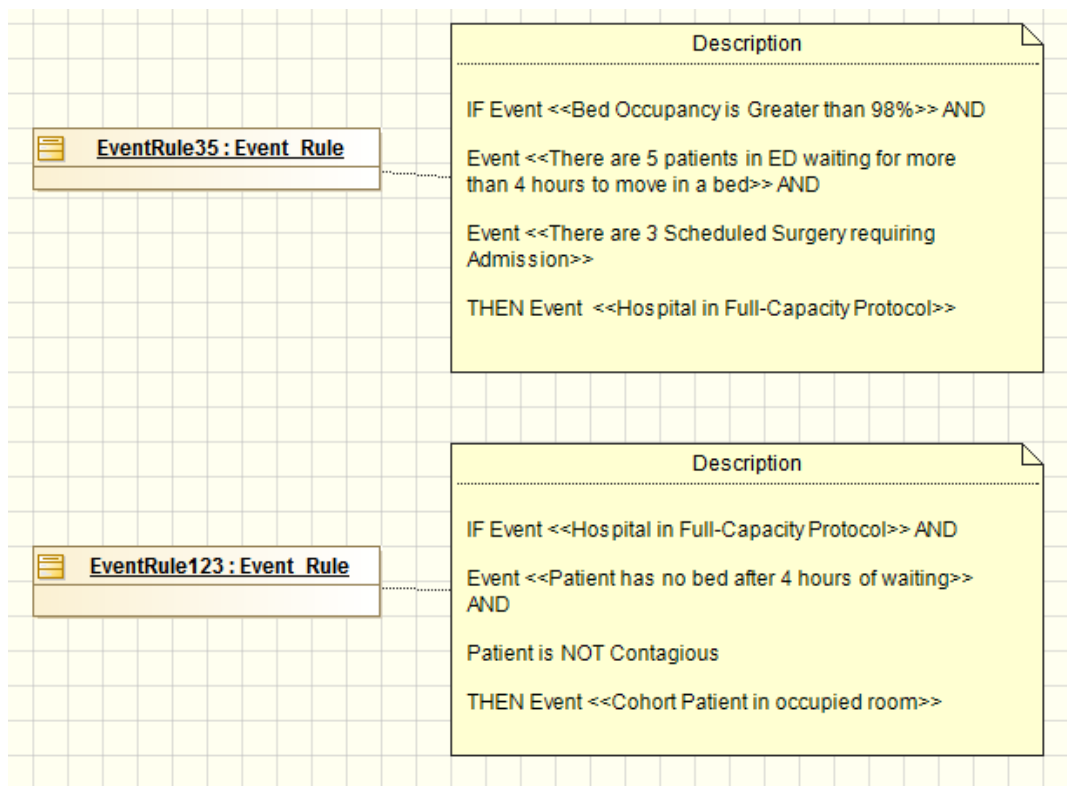


Figure 4-35 Examples of Event Rules

The knowledge Rules are stored in the Rules Repository Component, and are managed by the Rules Management Component, and are executed by the Rules Engine Component. Typically, the knowledge Rules implement Policies, Guidelines, and Knowledge Sources.

Figure 4-36 gives an example of knowledge Rules. If the hospital is in Full-Capacity Protocol, the patients (who are not contagious) are cohorted into double-bed rooms first, and then into single-bed room.

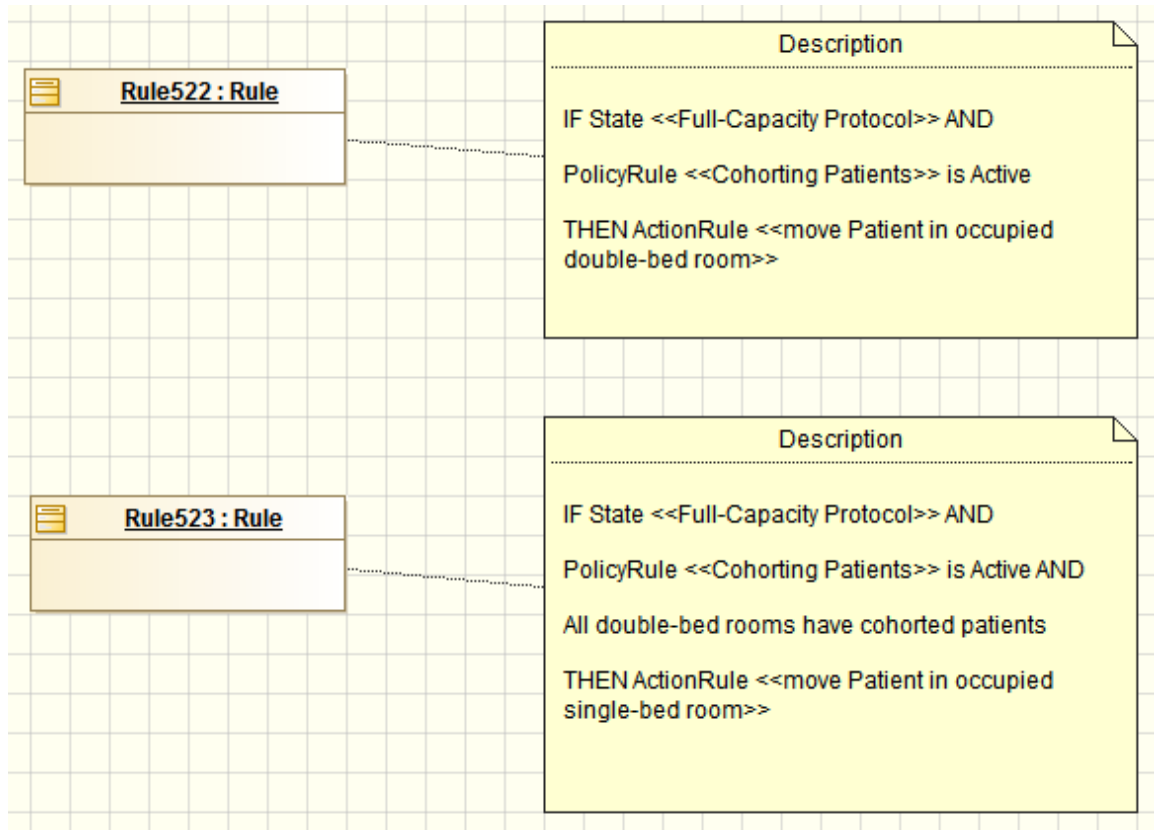


Figure 4-36 Example of knowledge Rules

Note: The examples above are written in pseudo-code for readability. The actual validation has been done with DROOLS using the DROOLS Rules Language. The DROOLS team has committed to support DMN in 2015, but this capability is not available yet, as of April 2016 when this thesis work has completed. DMN is currently supported by several commercial tools (see section 2.4.4), but it not fully available on open source tools.

4.4.5 Model Weaving

The weaving of UML, BPMN, DMN, SOAML, HL7, and Optimization/Simulation/MCDA models is done according to the Views described in Section 4.3. The Primary model is the one that Clinicians would most likely use to represent the problem at hand. The Secondary models add more information to the Primary model, along a different problem dimension.

SOAML and HL7 are UML Profiles, so they are generally included in the description below about UML models, except when explicitly noted.

Table 4-11 below shows the Primary and Secondary models for each COM Model view:

Table 4-11 Primary and Secondary models for each COM View

	UML	SOAML	HL7	BPMN	DMN	Optimization Simulation MCDA
Process	S	S		P	S	
Structure	P				S	
Function	S	P	S	S	S	
Event	P		S		S	
Knowledge	S		S		P	
Organization	P				S	
Engineering	S					P

P = Primary; S = Secondary

For instance, in a Process view, the primary model is a BPMN one. A secondary DMN model might be woven in as a decision task. Another secondary SOAML model might be woven in as an activity. A third secondary UML model will be woven in to describe a complex process data structure.

Table 4-12 below shows how the Secondary model is woven into the Primary model: for instance, a BPMN process segment could be woven as is into a SOAML model, or could be encapsulated in a SOAML Activity Diagram (see example in Figure 4-37)

For the Engineering View, the Secondary UML model is weaved into the Primary Optimization/Simulation/MCDA models via an interface script.

Table 4-12 Weaving of Secondary model into Primary model

Secondary Primary	UML	BPMN	DMN
UML (including SOAML)		UML/SOAML Activity Diagram, or BPMN Model (remain as is)	UML/SOAML Operation implemented as SOA service
BPMN	BPMN data structure		BPMN Activity implemented as SOA service
DMN	DMN data structure	DMN Boxed Function implemented as Java code	

The weaving of all models is done manually by the Analyst, using the COMP Modeling Tool. It is done at the Participant and Component levels. The weaving is based on names; therefore, Analysts have to ensure that names are aligned appropriately. Currently, there are no traceability mechanisms to ensure that models remain aligned when one has to be modified; this has to be done manually.

Figure 4-37 below gives an example of a SOAML Primary model representing the Service Line Management function view, into which Secondary models are weaved in, starting from the top and going clockwise:

1. The UML Components are woven into the Service Line Manager Participant
2. The DMN Rules are woven into the Rules Manager Participant
3. The UML COOM Packages are woven into the Blackboard Manager Participant
4. The DMN Event Rules are woven into the Event Manager Participant
5. The BPMN Process is woven into the Process Manager Participant

The weaving mechanism does not necessarily mean that a transformation of one model into another occurs:

- For instance, the BPMN Process in Step 5 could be kept as is: it is then simply executed by the BPM_Engine_Component of the Process Manager Participant, and communicates with the SOAML Activity via events.
- In another case, the BPMN Process could be encapsulated as a sub-process into a higher-level SOAML Activity Diagram which requires less details than what the BPMN model gives.
- Finally, a model transformation could take place when, for instance, a legacy BPMN care process has to be replaced by a simpler one which could be modeled as a UML/SOAML Activity Diagram.

The weaving points have been designed in (we called it Model Weaving by Design), thus preparing the foundation for the model weaving to be automated in future work (see Section 7.2).

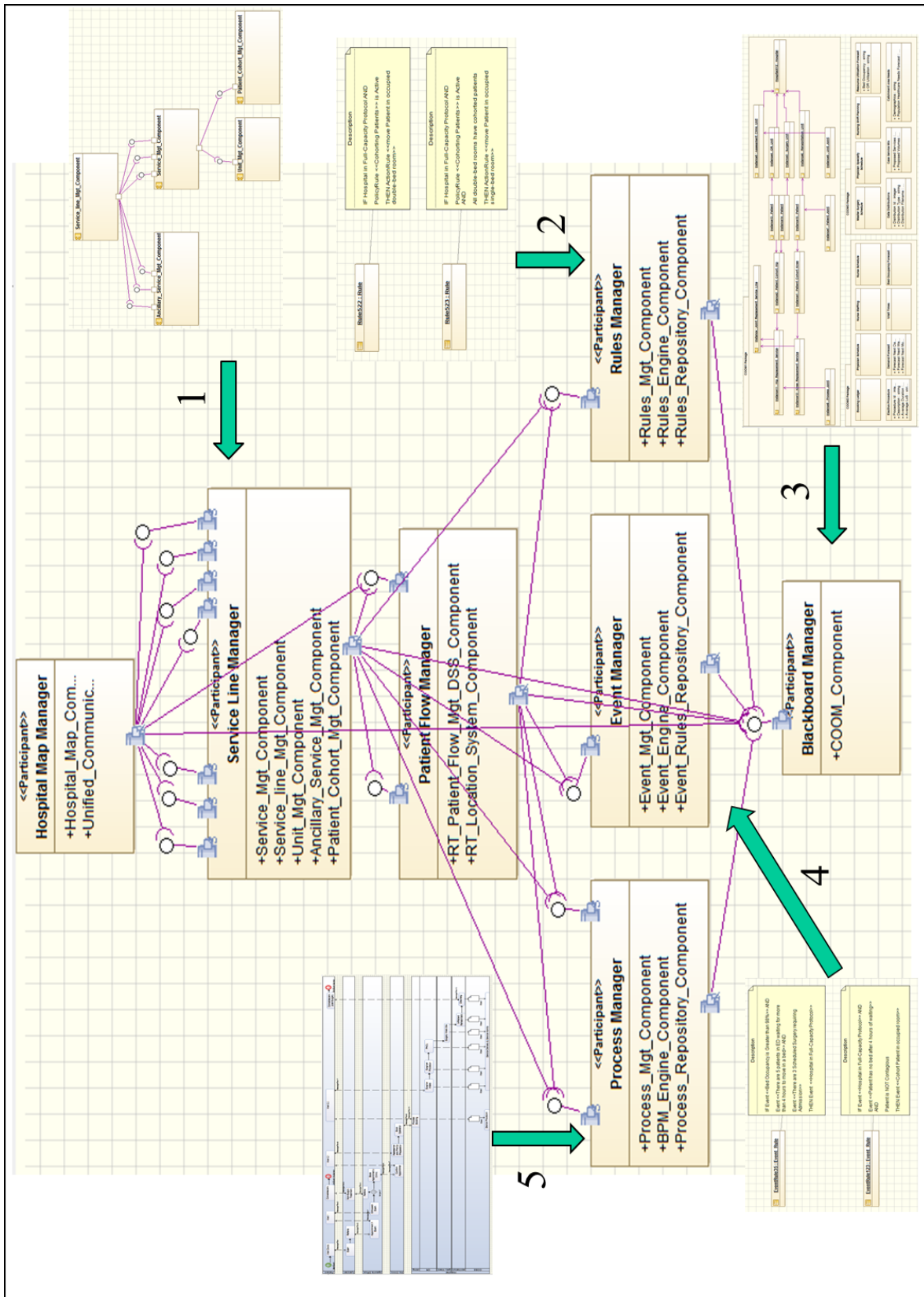


Figure 4-37 Example of Model Weaving

4.4.6 Recap: From COM models to UML/BPMN/DMN models

Table 4-13 recaps the mapping and transformation from the COM Models (on the left side of the table) to the UML/BPMN/DMN Models including the COOM and SOAML Models (on the right side of the table). For each of the 7 Views, a list of UML, BPMN, DMN, COOM, and SOAML models are listed. This list is not exhaustive yet, as only a deployment in several hospitals over some extended period of time could validate.

Table 4-13 From COM Models to UML/BPMN/DMN Models

COM Models			UML/BPMN/DMN Models			
Views and Foundation Classes	Derived Classes	UML Models	BPMN Models	DMN Models	COOM (UML Objects)	SOAML (UML) Models
Clinical Service (Generic)	Clinical Service (for hospital XYZ)	(Generic and for hospital XYZ)			(for hospital XYZ)	(Generic and for hospital XYZ)
Joint Replacement Service	Hip Replacement Service Knee Replacement Service					Hospital Map; Unified Communications
Function View						
Service Line Mgt	Service Provisioning; Service Management	Service Provisioning; Service Management		DMN rules for Service Provisioning & Management	COOM1 Object Model of service provisioning & management	Clinical Service Manager; Ancillary Service Manager; Stubs for Custom Code
Demand & Capacity Mgt	Demand Smoothing; Demand Prediction; Capacity Scheduling; Capacity Allocation; Master Surgery Scheduling; End-to-end Patient Flow Mgt	Demand Smoothing; Demand Prediction; Capacity Scheduling; Capacity Allocation; Master Surgery Scheduling; Predicted Booking; Real-time Booking; Allocated Capacity; Real-time Capacity; Patient flows; Patient location	Capacity Allocation and Optimization	Knowledge Source for Demand & Capacity Management	COOM1 Object Model of Demand for all Units; COOM2 Object Model for Booking; COOM1 Object Model of Capacity for all Units; COOM2 Object Model of scheduled capacity	Demand Mgt DSS; Capacity Mgt DSS; Master Scheduling; Full-Capacity Protocol DSS; Real-Time Demand Capacity mgt; Patient Tracking; Stubs for Custom Code
Supply Mgt	Case Cart Mgt; Inventory management	Case Cart Mgt; OR Inventory; Procedure Cards	Monthly re-stocking; Rush ordering	DMN rules for inventory management	COOM2 Object Model for short-term supply scheduling	Supply Management; Capacity Mgt DSS; Stubs for Custom Code
Performance Mgt	Performance measurement; Event notifications; Real-time analysis; Historical analysis;	Performance measurement; Event notifications; Real-time analysis; historical analysis; performance reports; Performance events; Indicators & Dashboards		Knowledge Source for operational performance management	COOM1 Object Model of operational performance management; COOM2 Object Model of historical performance analysis	Operational Business Intelligence; Historical Business Intelligence; Stubs for Custom Code
Qoc, Risk, & Safety Mgt	Adverse Event Management; Infection Control	Surgery adverse event management; Infection Control on Surgery units; Event notifications	Root Cause Analysis of adverse event	Knowledge Source for Adverse Event Management and Infection Control	COOM1 Object Model of adverse event impact on Clinical Operations	Adverse Event Management; Infection Control; Stubs for Custom Code
Accounting Mgt	Weighted Case Costing	Case Accounting; OR overtime analysis; Accounting events; Event notifications		DMN rules for Accounting Events	COOM2 Object Model of Weighted Case Costing analysis and impact on Clinical Operations	Case Costing; Accounting Mgt; Stubs for Custom Code
HR Mgt	Absenteeism analysis; Real-Time staffing	OR Absenteeism analysis; Real-time staffing in OR and Surgery; Support to Staffing-to-Census		DMN rules for Real-time Staffing	COOM1 Object Model of real-time Staffing; COOM2 Object Model of Staff Scheduling	Staffing Mgt; HR Mgt; Capacity Mgt DSS; Stubs for Custom Code

Knowledge View Knowledge Sources (used in COSS BlackBoard)	Knowledge Source for Demand & Capacity Mgt	uses Hospital Organization UML models		DMN Rules for Demand & Capacity Management	COOM1 and COOM2 Object Models for Demand & Capacity Management	Demand Mgt DSS; Capacity Mgt DSS; Full-Capacity Protocol DSS; Master Scheduling DMN rules engine
	Knowledge Source for Operational Performance Management	uses UML models for Performance Management		DMN rules for Operational Performance Mgt	COOM1 Object Model of operational performance management;	DMN rules engine; Operational Business Intelligence
	Knowledge Source for Adverse Event Management and Infection Control	uses UML models for QoC, Risk, and Safety Management		DMN rules for Adverse Event Management; DMN rules for Infection Control	COOM1 Object Model of adverse event impact on Clinical Operations	QoC, Risk, Safety Mgt; Infection Control; Adverse Event Manager; DMN rules engine
Policies	Full-Capacity Escalation; Surgery Cancellation			DMN rules accessed by Knowledge Sources		DMN rules engine
Care Pathways	Clinical Guidelines			DMN rules accessed by Knowledge Sources		DMN rules engine
Engineering View Service Line Optimization	OR Capacity Optimization; Master Surgery Schedule Optimization			DMN rules accessed by Knowledge Sources, applied on COOM3	COOM3 Object Model for Optimization	Engineering Tools
Service Line Simulation	Patient Flow Simulation			DMN rules accessed by Knowledge Sources, applied on COOM3	COOM3 Object Model for Simulation	Engineering Tools

4.5 COSBench

COSBench is an Eclipse-based software development environment, designed to generate COSS Modules, written in Java. It transforms the UML Components from the UML/BPMN/DMN Models into Java COSS Modules, in a one-to-one mapping. The UML Components also include Java Notes (source code as described in section 5.4.2). Then, custom Java code is added to the generated code if needed. The COSS Modules are then linked with the COSBench Libraries. The whole set constitutes the COSS. See Figure 4-38 below:

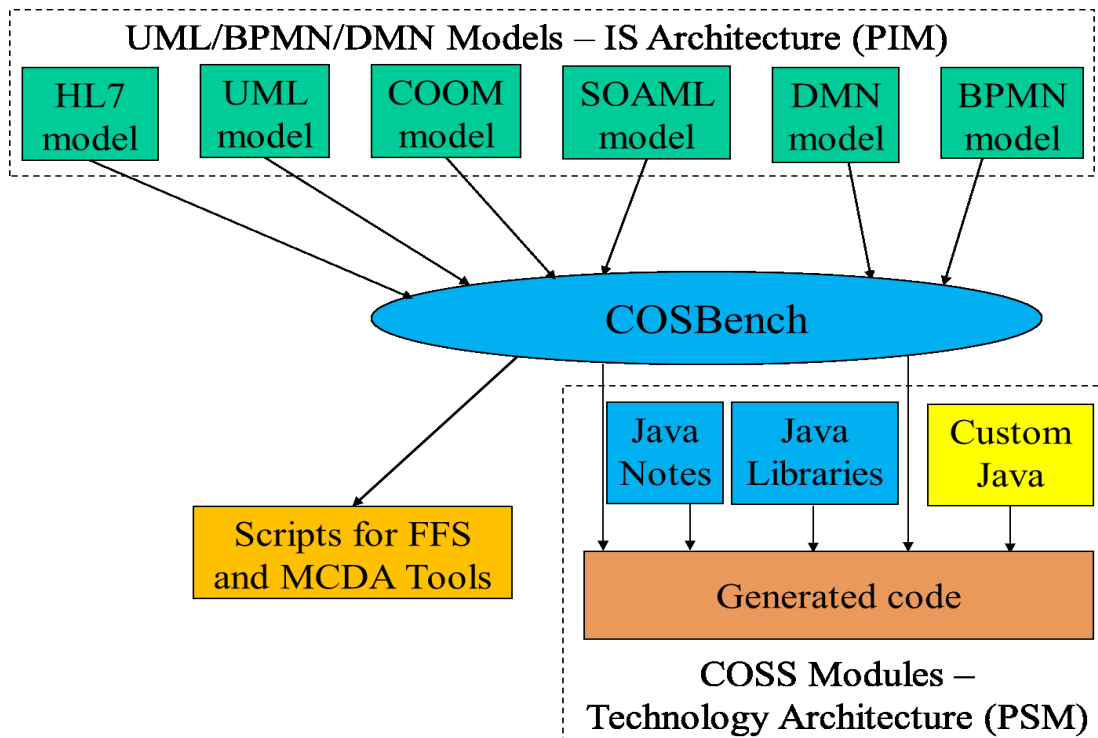


Figure 4-38 COSBench

4.5.1 COSBench Architecture

COSBench is composed of:

- A UML Model-to-Text generator. The text could be Java code or scripts for the Fast-Forward Simulation (FFS) and Multi-Criteria Decision Analysis (MCDA) tools.
- A DMN Model-to-Rules generator for the Rules Engine and the Event Engine
- A BPMN Model interpreter for the Process Engine
- A set of Java Notes and Libraries.
- FFS and MCDA Tools used by the COSS DSS, specifically the Full-Capacity Protocol DSS. They differ from the Engineering Tools of the COMP Tools because they are used at COSS run-time instead of modeling time.

The UML Model-to-Text generator is used to generate Java code from the COOM1, COOM2, and SOAML models. It is also used to generate scripts from the COOM3 model which will be used by the FFS and MCDA tools.

There is a one-to-one mapping between the UML Components in Section 4.4 and the COSS Modules of Section 4.6. We have made the design decision to use the UML Model-to-Java code transformation offered by the Eclipse tool suite (and related commercial products). Therefore, the code generation depends on the tool suite, and is described in section 5.4.2 in terms of a COSBench lab prototype used in our case study.

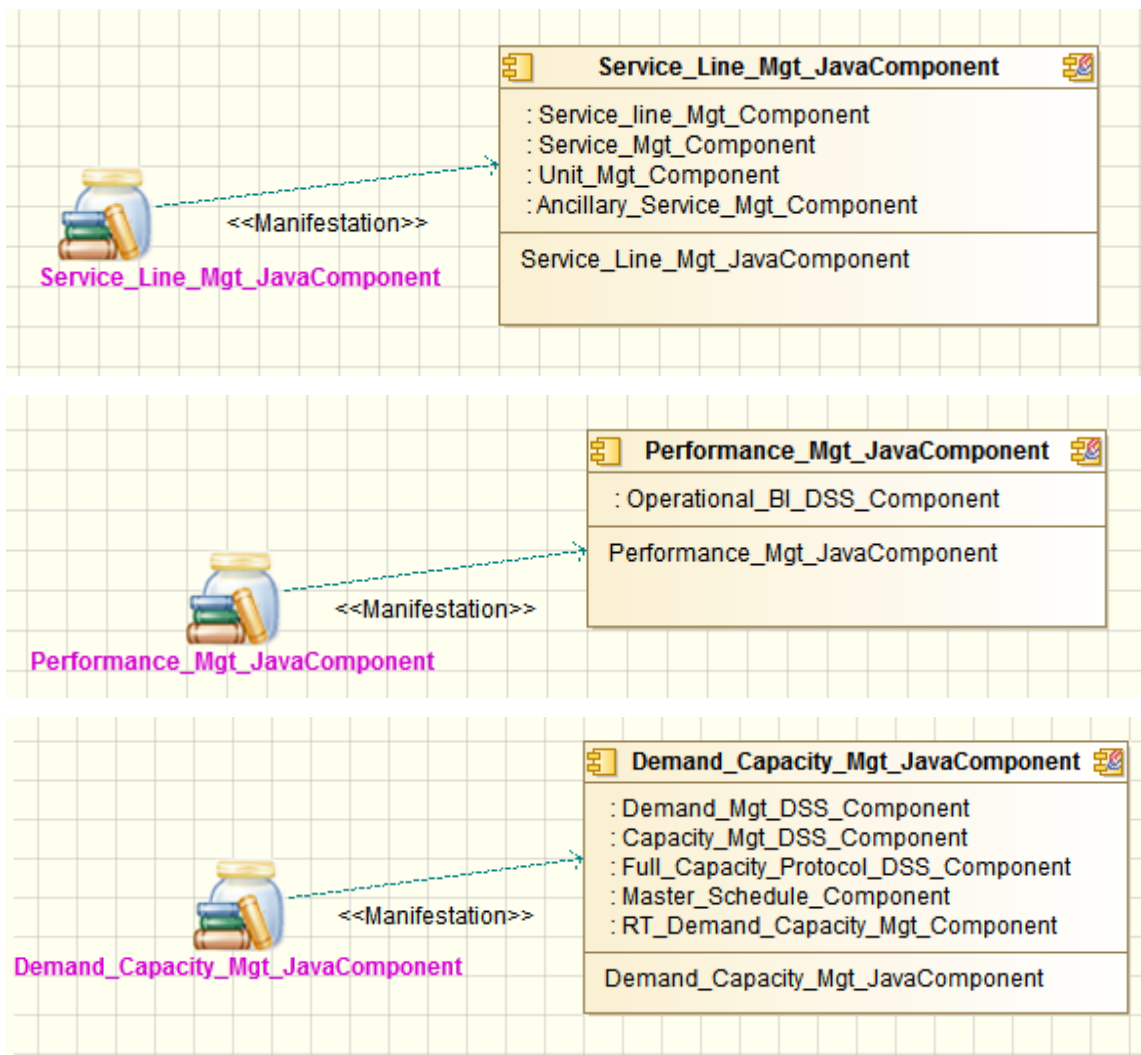


Figure 4-39 Examples of JAR File generation from UML Components

4.5.2 COSBench Development Process

The COSBench Development Process is for the Analysts and Software Engineers providing support to the Clinicians. COSBench is not designed to be used by Clinicians.

Unless the Analysts want to develop brand new COSS modules, the customization of the COSS for the hospital does not normally require the specification of SOA services. The generation of COSS Modules following customization for the hospital simply consists in

the Analysts running a set of scripts to re-generate, build and deploy the customized COSS.

The development of COSS Modules follows the steps below:

- Generation of SOA interface code, based on the UML Components
- Addition of Java Notes and COSBench Java Libraries
- Addition of custom code, if needed
- Build COSS
- Then, the BPMN models are loaded in the Process Engine, the DMN rules are loaded in the Rules Engine and the Event Engine
- The COSS is ready

4.6 COSS

4.6.1 Architecture of COSS

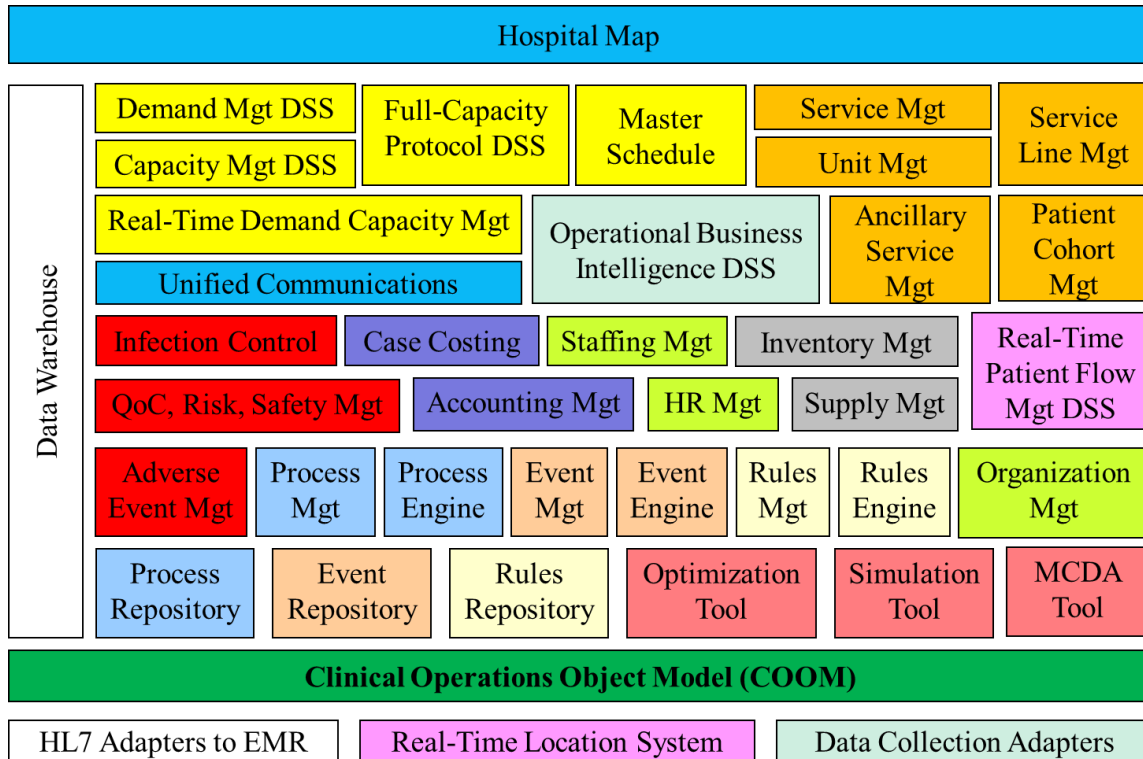


Figure 4-40 COSS Architecture Diagram

Since there are 39 UML Components, and with a 1-to-1 mapping with the COSS Modules, we have 39 COSS Modules (plus the Data Warehouse and the HL7 Adapters modules which were not considered in the modeling). Figure 4-40 above shows the COSS Architecture Diagram with the COSS modules which are grouped by color according to the 14 SOAML Participants they belong to (see section 4.4.1). A particular generated COSS might only use a subset of these depending on the service line(s) supported:

- Hospital Map Manager group including the Hospital Map and Unified Communications: these are User Interface applications. The Hospital Map is the main UI paradigm for the COSS; it displays a physical and logical map of the hospital, and the User can zoom in or out in order to access all information

- Service Line Manager group including Service Line Mgt, Clinical Service Mgt, Unit Mgt, Ancillary Service Mgt, and Patient Cohort Mgt. These 5 COSS Modules cover the provisioning, delivery, and monitoring of clinical services to patient cohorts, organized within a service line.
- Demand Capacity Manager group including Demand Mgt DSS, Capacity Mgt DSS, Full-Capacity Protocol DSS, Master Schedule, and Real-Time Demand Capacity Mgt. These 5 COSS Modules cover the real-time allocation of capacity based on the real-time demand in the hospital.
- Patient Flow Manager group including the Real-time Patient Flow Management DSS and the Real-Time Location System, for the real-time tracking and smoothing of patient flows through the hospital.
- Performance Manager group including the Operational Business Intelligence DSS, and the Data Collection Adapters, for real-time data collection, analysis, and reporting of operational performance indicators.
- Human Resources Manager group including the Staffing Mgt, the HR Mgt, and the Organization Mgt modules, for the real-time management of staff and schedules.
- Supply Manager group including the Inventory Mgt, and the Supply Mgt modules, for the real-time inventory control.
- QoC, Risk, and Safety Manager group including the Infection Control, Adverse Event Mgt, and QoC/Risk/Safety Mgt modules.
- Accounting Manager group including the Case Costing and Accounting Mgt modules, for the real-time case costing and financial control of the service line.
- Process Manager, Event Manager, and Rules Manager groups, each including a Mgt, Engine, and Repository modules.
- Engineering Tools Manager group including the Optimization, Simulation, and MCDA tools, for supporting Strategic and Tactical decision-making.
- Blackboard Manager group including the COOM module (COOM1/2/3)

The code generation of the COSS Modules depends on the tools used, and is described in section 5.4.2 on a lab prototype of COSBench.

The minimal COSS configuration is shown in Figure 4-41 below; these are all required COSS Modules for the COSS to be functioning properly. The Unified Communications and Real-Time Location System modules can be deactivated if needed.

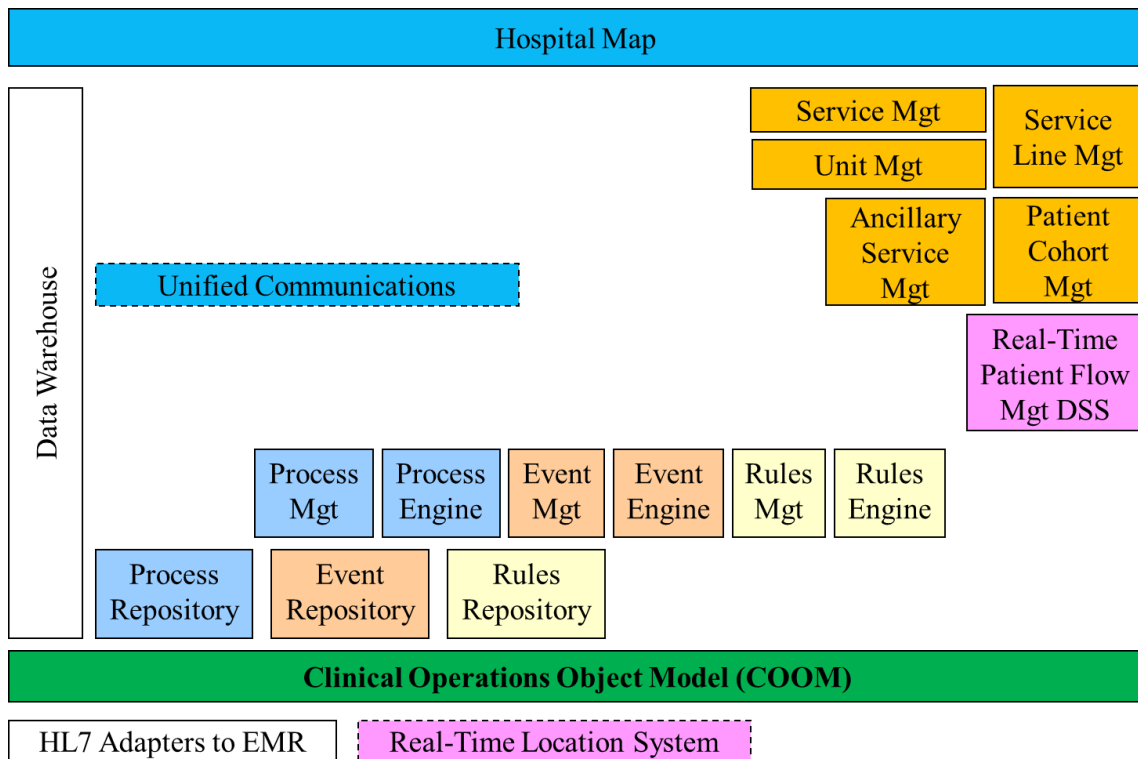


Figure 4-41 COSS Architecture Diagram in Minimal Configuration

4.6.2 Generic Design of a COSS module

Figure 4-42 shows the generic architecture of the COSS after generation with COSBench.

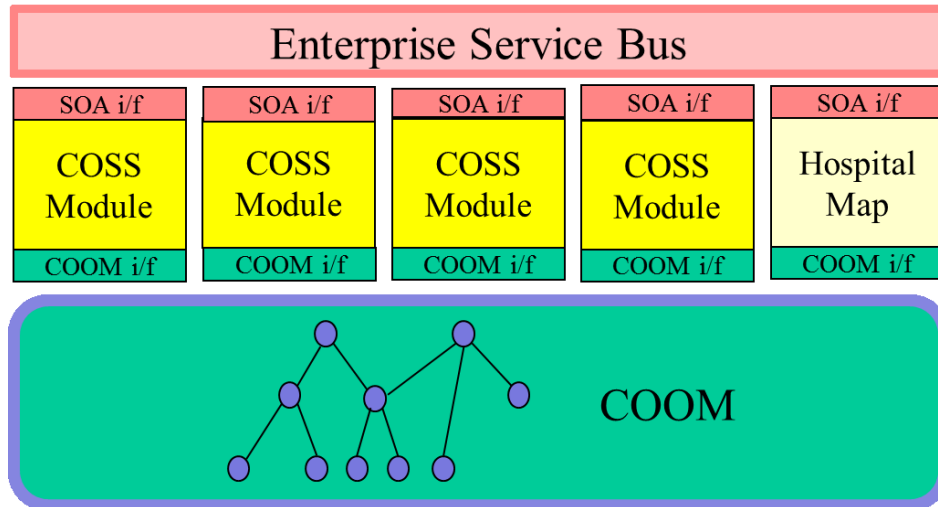


Figure 4-42 Generic COSS Architecture

By generic, we mean that every COSS Module complies with the same design pattern:

- All COSS modules are designed as software services, modeled using SOAML. They follow the request/reply interface of SOA when communicating with each other. This ensures loose coupling between modules.
- However, the COSS modules also have access to in-memory object model (COOM) which reflects the structure of a hospital and the clinical services it delivers. Shared memory is one of the strongest form of coupling between modules. This is done by design in order to support Model-Based Reasoning.
- Therefore, the COSS modules have 2 interfaces: the internal access to COOM, and the external SOA interface to provide/consume a service.
- COOM access is tightly controlled according to the Blackboard Architecture Pattern.

The COSS brings together Model-Driven Engineering, SOA, EDA, and Model-Based Reasoning (with the Blackboard Architectural Pattern):

- The COSS architecture is a hybrid between SOA (loose coupling) and tight integration via COOM (strong coupling). This is a key design decision.
- SOA: All COSS modules are supporting SOA interfaces and messaging.

- Blackboard: Most COSS modules reason about COOM objects and events, based on the Blackboard Architectural Pattern. COOM is the Blackboard, and the COSS modules are the Knowledge Sources working on the Blackboard. They communicate via the blackboard just for reasoning and data access, and via SOA interfaces for control and information passing. The Control function orchestrating the overall interaction is located in the Hospital Map.
- EDA: the COSS consumes real-time events coming in Streams, and also generates events, as specified in the Event COM Model. Events are processed by the CEP engine.
- MDE: COSS is generated from the COM Models built by Clinicians.

A COSS module can either be:

- A simple SOA Service, like the Real-Time Demand Capacity Service or Unified Communications Service
- Or a DSS which, on top of being a SOA Service, also provides decision support based on DMN rules described in Knowledge Models. A Knowledge Source is a special DSS type also doing reasoning on the COOM blackboard, like the Demand Management DSS, the Capacity Management DSS, and the Full-Capacity Protocol DSS.

A COSS module is composed of code generated from the COM Models, COSBench Java libraries, and custom code which are weaved together. The generic design of a COSS module includes the following components:

- Generated SOA interfaces for communication with the Hospital Map, other COSS modules and/or other information systems using HL7 messages
- Generated Interfaces to the COOM blackboard
- Generated Interfaces to the BPM engine, CEP engine, Rules engine
- COSBench Java libraries
- Interfaces for the access to the Data Warehouse
- Custom code

It is our objective that, at a more mature stage, the custom code would represent less than 10% of the overall COSS code, and that the COSS customization for a hospital is mostly done by customizing the COM Models and the UML/BPMN/DMN models, and then generating Java code with COSBench.

In the case where Users have a need to develop new COSS modules which do not already exist in the COMP Libraries, and to integrate them with the existing modules, here is how this could be done:

- Users can create a new COSS module by expanding the COOM model and expanding/creating a new SOAML model for the module. Users can also leverage the generic templates provided by COSBench.
- They generate code from the SOAML and COOM models
- They manually fill in custom Java code for generated stubs, and call Java Libraries
- The COSS module would likely produce and consume events, and therefore communicate with the CEP engine. A new event model might be required.
- The COSS module would provide new service management functionality and therefore, would communicate with the care processes and BPM engine
- The COSS module might provide decision support, and therefore communicate with the Rules engine. A new rule set might be required.
- Users then integrate their newly created COSS module with the other COSS modules and to the GUI applications (Hospital map, Clinical Service Manager, Unit Manager).
- The COSS modules communicate with each other using the SOA requests/replies
- The Java code for the new COSS module might be packaged into a Java Library which can be re-used by other Users. COSBench grows incrementally.

Finally, at the technology level, the COSS modules must also comply with the following:

- Multi-threaded environment: the COSS modules have to be designed to be thread-safe

- Java Monitors and Synchronization mechanism used on the COOM objects on the blackboard: the COOM objects are critical resources accessed by multiple threads

4.6.3 COOM at Run-Time

COOM has 3 models (Section 4.4.2) which are interconnected

- COOM3: Strategic and Tactical models drive Industrial Engineering tools
- COOM2: Operational off-line models drive COSS functions which are not real-time (short-term planning)
- COOM1: Operational on-line models drive COSS real-time functions

The 3 COOM models are composed of objects with different granularity, different roles, and different timespan. They typically do not overlap because there is a separation of concerns between them.

The COOM objects are modified by:

- External and internal events
- HL7 messages coming from EHR
- Sensor data (RTLS for instance)
- Users, via the Hospital Map and other user interface applications

When COOM objects are modified, this triggers the Rules Engine used by some COSS modules to fire some rules which:

- Send events
- Modify some COOM objects
- Send HL7 messages to other Clinical Information Systems and EHR
- Display/collect data from users
- Start some Actions

Rules are made for BPM decisions, CEP decisions, and DSS decisions. Because most rules understand the context they are operating in (i.e the specific area of the COOM

Blackboard they are working on), they either have a development-time, or acquire a run-time, knowledge of their COOM model.

Some other COSS modules do not use rules, but the principles are the same. They are multi-threaded, they monitor COOM objects and/or modify them, they generate events, start Actions, interface with the users, etc.

The blackboard control function is located in the Hospital Map; it is orchestrating the interaction between the blackboard knowledge sources.

One difference with a traditional Blackboard is that COOM1 and COOM2 blackboards present not only facts/data, but also the relationships between them. They embody additional domain knowledge which can be used by the Knowledge Sources for further inferences.

Another difference is in the simultaneous use of the COOM and the SOA messaging by the Knowledge Sources for communications and control. This gives a degree of flexibility that traditional blackboards did not have.

One concern has to be noted with the use of a Blackboard: since patient and hospital information resides in the Blackboard data structure, it becomes a single point of privacy and security risk. Future Work would have to consider adding an encoded access to the Blackboard.

4.6.4 Knowledge Sources and DSS

Some COSS modules play the role of Knowledge Sources in the Blackboard architecture. The Control function is located in the Hospital Map.

The Clinicians update the reasoning of the Knowledge Sources by updating the Domain-Knowledge Rule Sets in the COM Models

- Rules for process decision-making: executed by BPM engine
- Event Rules: executed by CEP engine
- Decision-making Rules: executed by Rules engine

DSS are simply sets of Knowledge Sources and Blackboard, working together to fulfill some specific functions.

DSS Reasoning:

- Models help Users and drive COSS to reason about optimal clinical service management
- COOM1, COOM2, COOM3: separation of concerns, based on COM Functions Table
- Blackboard Architectural Pattern, with Knowledge Sources
 - A set of Knowledge Sources fulfilling a specific role is called a DSS
 - All DSS access COOM Blackboard
 - DSS synchronously communicate with each other via SOA interfaces
 - DSS access COOM objects and send/receive events to/from CEP
 - DSS only read from COOM objects; they do not modify COOM which is modified/updated by external triggers
 - Use of rules to capture COM knowledge
 - Inferences are done by rules forward and backward chaining
 - Blackboard control function is distributed in UI Applications
 - DSS dynamically learns about new clinical/medical services, generally without requiring code to be written.
- Engineering models are not visible in the Blackboard, but play a critical role:
 - Simulation models (Strategic, Tactical, and Operational)
 - Optimization models
 - MCDA decision models

There are 5 foundation DSS which are described in the sections 4.6.5 to 4.6.8:

- The Real-Time Patient Flow Management DSS (RT-PFM DSS), which uses the Real-Time Location System
- The Operational Business Intelligence DSS
- The Demand Management DSS and Capacity Management DSS
- The Full-Capacity Protocol DSS.

The algorithms for these foundation DSS are residing in the COSBench Libraries, and do not result from COM modeling and then code generation. However, they do use processes and rules coming from the COM Models.

4.6.5 Real-Time Patient Flow Management DSS

The DSS, using the Real-Time Location System, enables a real-time monitoring and control of the patient progress along the care pathway. It interacts with the COSS Modules in the Process Manager, Event Manager, Rules Manager groups, and accesses COOM for inferences.

We take the example of an elderly patient with a hip fracture due to a fall, coming to the Emergency Department, late morning:

- The Patient is given an RFID wrist-tag at Triage; this enables the staff to track him throughout the hospital
- The Patient is put on the Hip Fracture care pathway by the Emergency Physician during the Physician Initial Assessment.
- The Hip Fracture care process is activated for the Patient by the COSS; his progress against the care pathway is now automatically monitored. Also, all wait times and performance indicators are automatically collected as seen in section 4.6.6.
- The Patient is sent to the Diagnostic Imaging Department for an X-Ray, and then comes back to the ED.

- Once the X-Ray results are available, the ED Physician is automatically informed, and when she comes into the ED Assessment Room where the patient is waiting, all the relevant data is automatically downloaded by the COSS on her tablet.
- A consultation with an Orthopaedic Surgeon is ordered. Again, when the Surgeon comes into the Assessment Room where the Patient is waiting, all relevant data is automatically downloaded by the COSS in her tablet.
- The Surgeon books the Patient for a procedure at 4:30PM using the COSS as seen 2 Sections below.
- Etc.

This scenario is possible because the DSS knows in real-time at what stage the Patient is on the Hip Fracture process. The Real-Time Location System knows in real-time where the Patient, the ED Physician, and the Surgeon are located. The correlation of these 2 sets of information done by the Event Engine enables the download of only the relevant data, at the right time, on the Physician's tablet when he comes to visit the Patient. See Figure 4-43 below. The correlation is also used by the Operational Intelligence DSS, the Demand Management DSS, and the Capacity Management DSS.

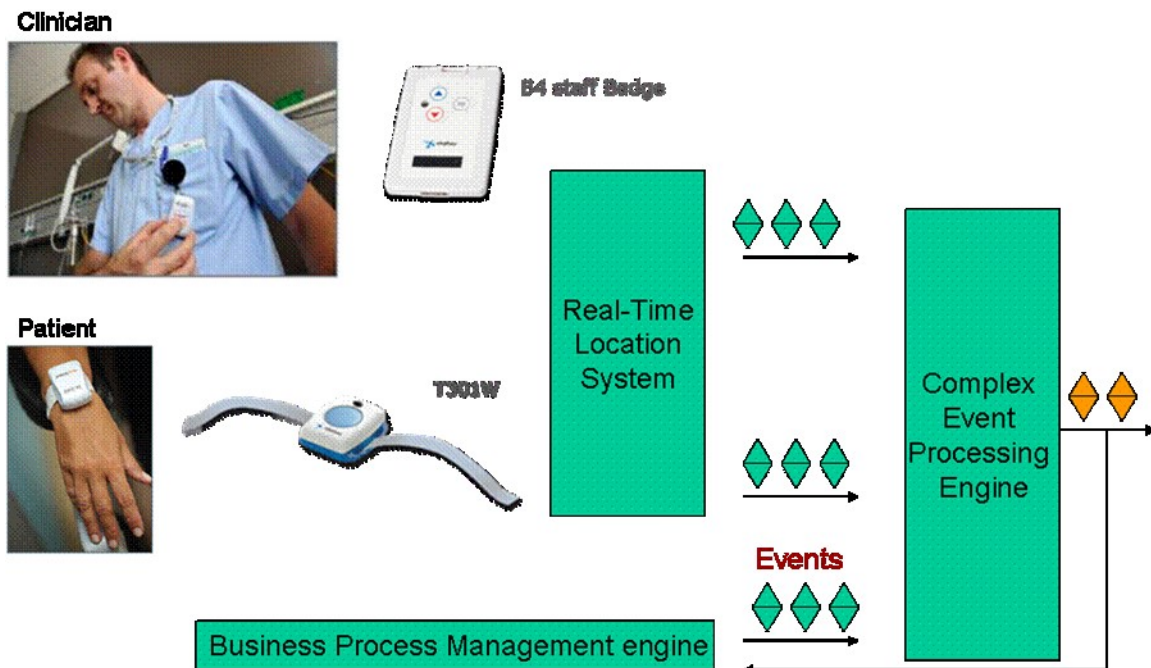


Figure 4-43 Real-Time Patient Flow Management DSS

The correlation and analysis of care process information with location information enables the creation of many other COSS functionalities.

Also, the event notifications that the Patient has been seen by the Emergency Physicians, has had an X-Ray taken, has been seen by the Surgeon, has been booked for a Hip Fracture surgery, etc, have been automatically sent to the COSS modules in charge of Supply Management (to ensure a joint prosthesis of the right type and size is available for a 4:30PM procedure), of Accounting Management (for the end-to-end real-time Activity-Based Costing), of QoC/Safety/Risk Management (for Infection Control monitoring).

4.6.6 Operational Business Intelligence DSS

Business Intelligence tools are being deployed across hospitals, but are largely used for historical and administrative reporting. There is a need for real-time Business Intelligence that can provide dashboards and metrics related to clinical care pathways in order to address operational challenges in meeting wait-times mandated by government funding agencies accreditation guidelines.

If we could measure wait times and service times automatically, without burdening the patients or the clinicians, we would then be able to provide a real-time dashboard on the hospital operational performance. This would enable the nurses in charge to make informed decisions in managing the patient flows.

However, patient wait times are usually very hard to measure automatically because we do not know for sure when they start and when they stop. Also, usually nobody tells us explicitly when a patient starts waiting. The best way, besides asking the patient herself, is to infer that the patient is waiting because we know that some task has just been done on the patient, according to the workflow, and she has not yet started the next task in the workflow. However, this should not be confused with the patient doing nothing because

he is recovering. The context will tell us whether the patient is waiting or simply recovering.

Figure 4-44 below describes an example of how we automatically compute the time a patient with Acute Coronary Syndrome (ACS) in ED waits for the ED Physician to re-assess him:

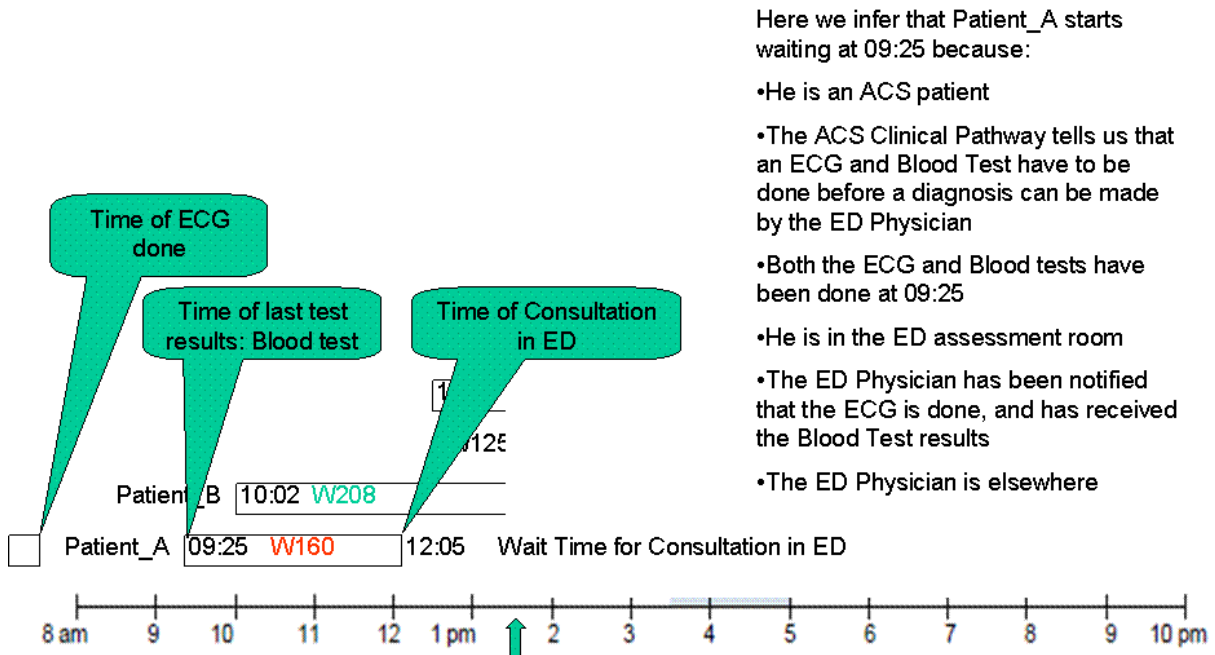


Figure 4-44 Data Collection for Operational Business Intelligence

- The patient is showing symptoms of Acute Coronary Syndrome (ACS) and is presenting in ED at 08:45AM
- The Triage Nurse gets the vitals signs, assigns a severity level CTAS 2, equips the patient with an RFID tag, and informs the ED Physician
- After an initial physical exam, the ED Physician prescribes an ECG and Blood Test to be done before a diagnosis can be finalized, according to the ACS Care Pathway
- Both the ECG and Blood tests have been completed at 09:25AM, and the results have been electronically communicated to the ED Physician who is attending other patients

- The patient is in one ED assessment room. We infer that the wait is starting because all tests prescribed by the Physician have been completed, the results have been communicated, and according to the ACS Care Pathway, the ED Physician has all the information he needs for the diagnosis.
- The ED Physician location is tracked automatically, and he comes back to the patient ED assessment room at 10:15AM to finalize the diagnosis
- We compute that the patient wait time for the ED Physician has been 10:15 – 09:25 that is 50 minutes.
- Such a wait time is acceptable for an ACS with severity level CTAS 2, but would not have been for a CTAS 1 case.

This example shows that in order to compute patient wait times, we need to have some domain knowledge about Care Pathways, and we have to correlate:

- patient and physician location events, coming from the RFID tags
- events generated by the workflow management system and by the EHR when the ECG and Blood Tests have been completed and the results communicated to the ED Physician
- user input from the ED Physician ordering an ECG and Blood Tests to be performed on the patient

This is described in Figure 4-45 below.

The Operational Business Intelligence DSS interacts with the COSS Modules in the Process Manager, Event Manager, Rules Manager groups; it accesses COOM, and interacts with the Real-Time Patient Flow Management DSS in order to automatically do this.

The support to decision-making is in what to do when, for instance, there is a realization that a patient wait time will breach soon, and when a unit performance indicators show a deteriorating trend. The Operational Business Intelligence DSS works with the other DSSs, using the Blackboard architecture, to present options to Nurses and Physicians.

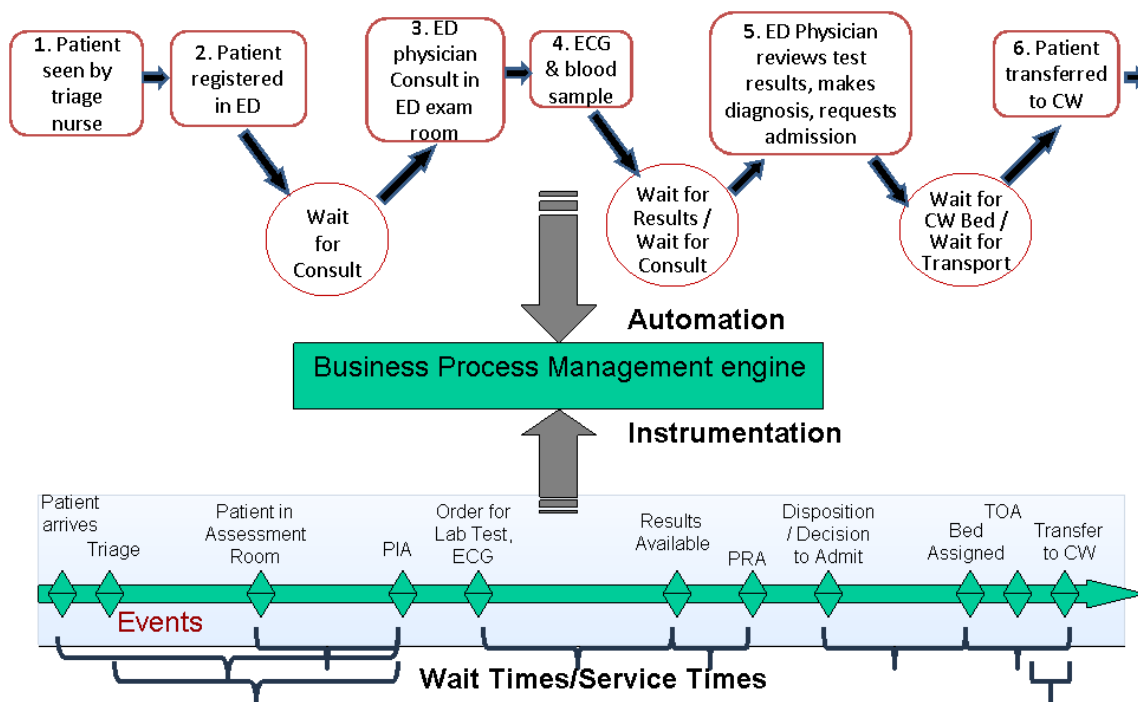


Figure 4-45 Correlation between Data Collection and Process Management

4.6.7 Demand Management DSS & Capacity Management DSS

The Demand Management DSS and the Capacity Management DSS work in tandem: the former is in charge of smoothing the elective demand and managing the emergency demand, while the latter is in charge of optimizing the hospital capacity in order to meet the demand at the highest possible Quality of Care while minimizing the cost. These tasks are complex by themselves, are inter-dependent, and should be done hospital-wide instead of unit-wide.

The Demand Management is complex because the elective and emergency patient flows impact each other. Counter-intuitively, the elective flows which are totally under the hospital control (because the elective patients are scheduled for treatment) are less well managed than the emergency flows on which the hospital has no control. The elective flows show a higher variability from one day to another than the emergency flows

[Litvak2010]. This has a big impact on bed occupancy in the units, and on the OR utilization.

The Capacity Management is complex because the non-smoothed Demand compounds the challenging task of allocating enough capacity in order to provide a high Quality of Care while minimizing the hospital costs [Litvak2010]. Another factor compounding the complexity is that many clinical tasks are manual, and there is a high variability between Clinicians performing the same tasks under the same conditions. The variability might be a factor of 3 to 4 (that is Clinician A would take 3 to 4 times more resources/time to perform a task than Clinician B under the same conditions). Finally, the capacity allocation has to be optimized for the entire hospital; today, because units work in silos, the optimization tends to be achieved for the unit and we are trapped in a local optima instead of achieving a global optima.

Our Demand Management DSS works on admission control for elective surgery with the objective to optimize OR utilization and ward bed occupancy, and avoid OR overtime. The DSS proposes timeslots for elective surgery by taking into account:

- the Surgeon's procedure duration in the OR,
- the predicted patient's Length of Stay in the Surgery ward post-op,
- the predicted ward occupancy on different days of surgery,
- the available timeslots for the Surgeon,
- the Surgeon's currently known workload on different days of surgery,
- the Surgeon's wait times for the given procedure, and
- the probability for Full-Capacity Protocol on different days of surgery.

The DSS knowledge is encoded into rules, and it works on the COOM2 blackboard.

In parallel with smoothing the future elective flows, the DSS also works on the management of today's emergency and elective flows. In case of a surge in emergency surgeries, the DSS might have to re-schedule today's elective surgeries to different times, based on OR availability and bed availability in the wards. For those real-time decisions, the DSS works on the COOM1 blackboard.

		Bed Status Report											
Feb 3rd, 2015 at 7:00AM													
		C4			C3								
Unit - bed capacity	A3 = 34	C4 = 30	Flex = 4	Med = 8	Surg = 16	Flex = 8	D3 = 40	A4 = 38	ICU = 12	MNB = 30	MH = 24	D4 = 30	
# occupied beds	32	30	4	15	9	8 med	40	38	8	15	22	30	
# unfunded beds (occupied/max)		1/3		2/3			0/1					0/1	
Off-serviced patients		1 sx					1 med			1 gyne, 2 sx			
# ALC		2		3				1				30	
# confirmed discharges for 2:00PM													
# possible discharges for 2:00PM													
Blocked beds (because of problem)													
# Closed OR (because of problem)	0												
# Same Day Admits (IN-AM) for today	10	1 gyne											
# Same Day Admits (IN-AM) for tomorrow	9	2 gyne											
# ICU Surge (off-serviced to PACU)	0												
# of ICU Transferables	1												
# of ED stretchers available	5												
# of ED Admits-No assigned bed	3	2 med- both tele, 1 MH											
# of isolations	52												
# of tele packs available	1												

Figure 4-46 Example of Bed Occupancy

Our Capacity Management DSS works on the allocation of beds, scheduling and staffing of Nurses, scheduling of Physician shifts, and allocation of equipment. The capacity allocation is optimized based on current and predicted bed occupancy across all units, predicted Length of Stay of patients, staffing-to-census objectives, isolation requirements, requirements for specific equipment. The capacity allocation also takes into account the variability between individual Clinicians in the scheduling. The DSS knowledge is encoded into rules, and it works on the COOM2 blackboard in tandem with the Demand Management DSS for future capacity allocation. The DSS works on the COOM1 blackboard for real-time capacity allocation, and collaborates with all the other DSS.

The global optima versus local optima challenge is handled with the concept of Flex beds and Flex Nursing. A small pool of resources is dedicated to increase the flexibility of the entire hospital: Flex beds can be open and closed in specific units in real-time, depending on the needs, and a small group of Nurses are trained to work in both the Medicine and Surgery wards, for instance, so that they can move from one to another with minimum

notice. The Medicine Physicians, for instance, do practice geographic rounding in given units, but can temporarily round on some of their patients who have been moved to a different unit because of bed availability. This is an example where the HR Organizational Effectiveness has a direct impact on clinical care when supported by the right information system.

4.6.8 Full-Capacity Protocol DSS

Despite the best possible management of Demand and Capacity, there may be times when a surge of patients arriving in the hospital happens and bottlenecks start building up. Usually, this is seen in the Emergency Department even though the actual root cause of the bottleneck might be in another unit further down the flow stream. When this happens, a Full-Capacity Protocol is called either in one unit or through the entire hospital. The staff in charge of Access & Flow Management are faced with the task of making the best possible decision in order to get rid of the bottleneck in the most optimal way possible. Today, the decision-making process is manual and ad hoc, based on historical and incomplete data. Even with real-time performance data as described in the previous section, the decision-making process is still manual, and usually optimal for the clinical unit only (instead of for the entire hospital), and usually made during a time of high stress.

Our objective is, based on the operational performance information collected in real-time, to support the decision-making process of the Clinicians by suggesting possible actions to remedy to the bottlenecks in the patient flows across the hospital. This support must take place in real-time, based on data, and should be optimal for the entire hospital instead of just one unit.

The decision-support algorithm is the following:

1. Situation Perception: analysis of possible triggers for Full-Capacity Protocol
2. Situation Comprehension: end-to-end analysis of bottleneck across all units

3. Situation Projection: Fast-Forward Simulation to get a sense of how the bottleneck will evolve in the near future
4. Decision to activate the Full-Capacity Protocol – level Yellow
5. Situation Resolution for level Yellow: Recommendations for Actions (level Yellow); Multi-Criteria Decision Analysis
6. Situation Monitoring (done by Operational Business Intelligence DSS)
7. Escalation, if needed, from level Yellow to Red
8. Situation Resolution for level Red: Recommendations for another set of Actions (level Red); Multi-Criteria Decision Analysis
9. Situation Monitoring
10. Full-Capacity Protocol de-activated

These actions typically belong in 3 groups:

- Shape the patient demand: transfer patients to another hospital, cancel elective procedures, for instance
- Increase capacity: open flexible beds, add more clinical staff, cohort patients
- Mitigate the impact of the bottleneck: do off-servicing by sending cardiac patient to a Medicine ward instead of a Cardiology ward, for instance

These actions are not incompatible with each other; many complement each other. Therefore, the user may decide on implementing a set of actions in a sequence.

The Actions (level Red) are more drastic than Actions (level Yellow), and they both are not normally authorized when there is no bottleneck (that is, the Demand Management DSS and Capacity Management DSS cannot normally recommend those Actions).

Some of these actions may have conflicting impacts on corporate goals: for instance, adding more Nurses may increase Safety and Quality of Care, but will also increase cost and negatively impact the corporate requirement of having a balanced budget at year-end. Another example is cohorting patients in the same room in order to create space for incoming patients; this usually negatively impacts Patient Satisfaction. In order to

maintain as much balance as possible between these conflicting objectives, a Multi-Criteria Decision Analysis is done before recommending some Actions.

The Full-Capacity Protocol DSS architecture is shown in Figure 4-47 below:

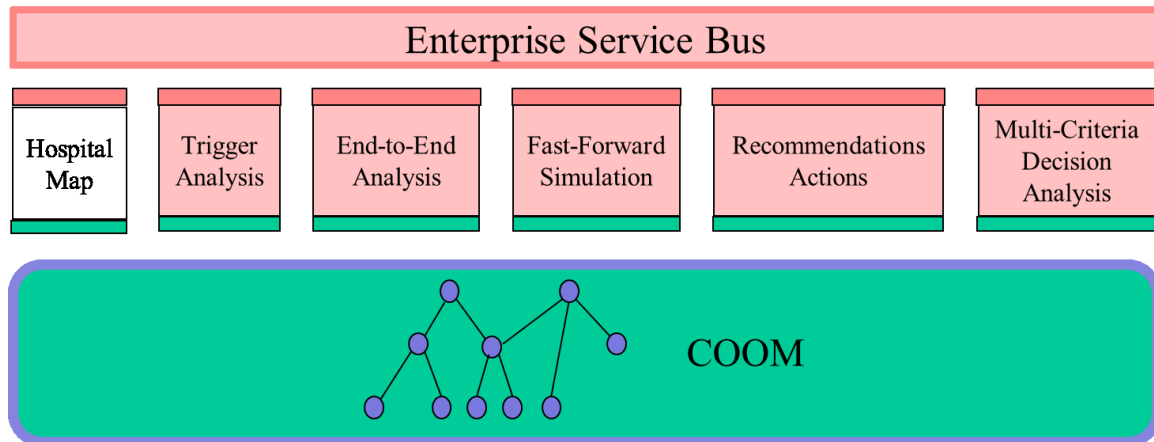


Figure 4-47 Full-Capacity Protocol DSS Architecture

The DSS modules work together on COOM, and the coordination is done by the Hospital Map. The Trigger Analysis, End-to-End Analysis, and Recommendation for Actions modules are based on Rule sets working on the COOM1 blackboard. The Fast-Forward Simulation module uses the Discrete Event Simulation tool and works on the COOM3 blackboard which is connected to COOM1. The MCDA module uses the MCDA tool and also works on the COOM3 blackboard.

The Full-Capacity Protocol DSS collaborates with the Demand Management DSS, the Capacity Management DSS, the Operational Business Intelligence DSS, and the Real-Time Patient Flow Management DSS, via the COOM1 blackboard and SOA messaging, in order to ensure a coordinated solution.

4.6.9 Incremental Development

How is COSS supporting additional services and service lines?

- New services and service lines would require the Clinician to model:
 - Service Line, Clinical Service, and Patient Cohort
 - Process View
 - Structure View
 - Event View
- Typically, the Clinician would also update the Knowledge View, in parallel with the above, as new Guidelines and Policies are developed for the new services/service lines.
- If new positions like the Service Line Director and/or Service Line Nursing Coordinator are created, the Organization View would be updated.
- In rare cases, the Function View may need to be updated.
- The Engineering Tools would have been used already for the decision-making about creating the new services/service lines

The COSS will dynamically support the new services as follows:

- Service Line, Clinical Service, Patient Cohort, Structure View, and Organization View: the models are loaded into the COSS. The Dynamic EMF capabilities (Reflection API) of Eclipse that COSS is using, enable a generic access to the models without needing any generated code.
- Process View: The new process models are loaded into the Process Repository for processing by the Process Engine. A new process would appear as new swim lanes.
- Event View: The new event models are loaded into the Event Repository for processing by the Event Engine. The Dynamic EMF capabilities (Reflection) of Eclipse that COSS is using, enable a generic access to the event models without needing any generated code.

- Knowledge View: The new rules are loaded into the Rules Repository for processing by the Rules Engine.
- The Dynamic EMF (Reflection API) approach, described in [EMF], takes up more memory and is slower than the code generation approach, but enables the dynamic integration of new services, unknown at COSS development-time. This enables the COSS to learn about the new services/service lines without having to re-generate the code and re-build the COSS.
- If new code is required for the new models above, it would be developed as Java Notes in the UML Components (see section 5.4.2). This would require code re-generation and a new COSS build. There is no dynamic learning in this case.
- Now, the Function View: In the rare cases when the new clinical services/service lines require new functions which do not already exist in the Function View, some new UML Components with new SOA services would have to be modelled, and some custom code would have to be developed. The COSS would have to be rebuilt. There is no dynamic learning; this is the most complex case of incremental development.

4.7 COM Development Methodology

Here is the sequence of steps to build COM Models, transform them into UML/BPMN/DMN Models, and then generate COSS Modules in order to support a service line:

- Choose the COM Functions Table coverage for the service line: this will determine the Function View, and the levels of decision-making that are supported
- Select the COM Enterprise Architecture Diagram coverage; that is, decide on QBP/Care pathways (Process View), Units (Structure View), and matrixed organization with roles & responsibilities (Organization View).
- The other Views (Event, Knowledge, Engineering) will be decided upon next, as a consequence of the previous decisions.

- Build COM Models accordingly, by using the COM Models Template to specialize for Service Lines: examples for Joint Replacement and Cardiac Procedures
- Use the mapping between COM Models to SOAML Participants in order to select the Participants and their UML Components.
- Design COOM UML Information Model; this will become the COSS Blackboard. For this, use the examples of COOM for Joint Replacement and Cardiac Procedures
- Design Processes, using BPMN. For this use the examples of Processes for Joint Replacement and Cardiac Procedures
- Design Event Rules, using DMN. For this, use the examples of Event Rules for Joint Replacement and Cardiac Procedures
- Design knowledge Rules, using DMN. For this, use examples of Rules for Joint Replacement and Cardiac Procedures
- Do Model Weaving between UML, BPMN, DMN models
- If needed, customize the UML Components and their SOA services.
- Generate Java COSS Modules, according to the 1-to-1 transformation of Components.
- If any, load the custom Java Notes and custom code following the customization.
- Load the COSBench libraries.
- Build the COSS.

4.8 Summary of the COM Enterprise Architecture

The main components of the COM Enterprise Architecture are:

- The COM Models describe the Business Architecture layer of the hospital TOGAF Enterprise Architecture. The COM Models are built using the COMP tools.
 - COMP is a Domain-Specific Modeling Language, with a MetaModel.

- COMP covers the Business Architecture of the hospital TOGAF Enterprise Architecture
- COMP is implemented as a UML Profile
- COM Functions Table describes how the COM domain is structured functionally and by decision levels.
- The COM domain for the hospital is specified by the COM Enterprise Architecture Diagram, that is 7 Views which constitute the COMP MetaModel: Process, Structure, Function, Event, Domain Knowledge, Organization, and Engineering.
- Engineering View is used at the Strategic & Tactical levels for optimization, simulation, and multi-criteria decision analysis.
- The COM Models are then transformed into UML/BPMN/DMN Models, including COOM and SOAML models, using the COMP Modeling Tool.
- The COSS, customized for the hospital, is generated from the UML/BPMN/DMN models using COSBench. It is designed and implemented following the Model-Driven Engineering approach.
 - COSS is based on both the SOA and EDA architectures.
 - COSS uses Model-Based Reasoning, with the Blackboard Architectural Pattern.
 - COOM is the blackboard itself, accessed by rule-based Knowledge Sources.
- The Clinicians are customizing the COM Models for their hospital. The Health Informatics Analysts are customizing and generating the UML/BPMN/DMN models for their hospital, from the COM Models, following guidelines we are providing. The customized COSS is then generated and configured automatically by COSBench.
 - If there are no changes to the SOAML definition, there is no need for the Users to write any Java code (Generated Java code + EMF Reflective API, in order to access COOM). The COSS has to be rebuilt though.

- If there are changes to the Function View, it is likely that there are changes to the SOAML definition, and therefore, some Java code has to be written.

5 Case Studies

5.1 Overview

5.1.1 Overview of the Case Studies

In this section, we describe five case studies that were used to validate our thesis. The first two use cases were developed using our COM models based on our COM Functions Table and COMP, but without the availability of COSBench to generate the COSS.

In our first case study in section 5.2, a prototype of a COSS for Cardiac Procedures service line, including the models, was manually developed. The work was done while I was at the William Osler Health System.

In our second case study, in section 5.3, a lab prototype of a COSS for the Joint Replacement service line, including the models that were used as illustrations in chapter 4, was manually developed, based on the work done with the clinical teams of Queensway-Carleton Hospital and the Hopital Montfort.

In our third case study in section 5.4, lab prototypes of the COMP Modeling Tool and COSBench were built in order to demonstrate the feasibility and evaluate the benefits of model-driven generation of COSS over the manual development that was done in our first two case studies.

In the fourth case study in section 5.5, an architecture analysis has been undertaken to ensure the underlying mechanisms of the COM Platform can be generalized to support, not only Cardiac Procedures and Joint Replacement service lines, but all service lines in a hospital. We are also analyzing the generalization to other types of hospitals. The technique used is Architectural Inference [Wieringa2013].

Finally, in our fifth case study in section 5.6, a business analysis is done of a hospital transformation to value-based hospital, without and with our COM Platform. This business analysis was done based on combined public data from all 3 hospitals.

5.1.2 Overview of the Hospitals

William Osler Health System (Osler):

Osler is a very large community hospital in Brampton, Ontario, with around 700 beds over 3 sites. The research focus was on managing flows of cardiac patients along the continuum of care, and on the process improvement of the Emergency Department which has the highest volume in Ontario. The case study is on a Cardiac Procedures service line.

Queensway-Carleton Hospital (QCH):

QCH is a large community hospital in Ottawa, Ontario, with around 270 beds. The research focus was on the Emergency Department, the Medicine Department, and the Surgery Department. The case study is on a Joint Replacement service line.

Hopital Montfort (Montfort):

Montfort is a large community and teaching hospital in Ottawa, Ontario, with around 250 beds. The research focus was on the Surgery Department and on the Medicine Department. The case study is on a Joint Replacement service line.

5.1.3 Context for the Case Studies

These case studies are based on actual work done on transformation towards value-based at each of the 3 hospitals described in the previous section. No case study has been achieved with the entire COM Platform, but with pieces of it (building the entire COM Platform was not in the scope of this thesis, nor within the capacity of a single Designer/Researcher). However, the mechanisms underlying the entire COM Platform have indeed been validated by the case studies in a realistic way.

Action Research complements Design Science Research with work in the real environment. I spent 6 years working as a Consultant at the 3 hospitals, in the Emergency Department, Internal Medicine, Cardiology, and Surgery as part of teams, including hospital executives, strategically working on the transformation towards a value-based hospital.

Following the Action Research approach, I have clearly separated my 3 roles of Consultant, Designer of Artifacts, and Researcher while at the same time ensured they were leveraging each other. As a Consultant in the hospitals, I was guiding the Model-Driven transformation of the hospitals as if the entire COM Platform was available. A lot of manual, painstaking work was done to emulate the existence of the COM Platform components when they were not available. This has helped me, as the Designer, to better understand the requirements for these COM Platform components. This has enabled me, as the Researcher, to validate the Research Hypotheses in a real-life practice environment.

To summarize my 3 roles:

- Consultant, to help the hospital progress in its transformation towards value-based hospital; this includes organizational, process, and IS redesign. This is done via paper analysis and recommendations, and manual execution of a transformation strategy. This is Action Research for the Relevance Cycle of Design Science Research.
- Researcher, to investigate new knowledge based on observation and experimentation, in order to address the Research Question of my thesis. This is Action Research for the Rigor Cycle of Design Science Research.
- Designer of artifacts, in order to investigate technical challenges and prove the feasibility of the COM Platform: COMP Tools, COM Models, UML/BPMN/DMN Models, COSBench, and COSS.

5.2 Case Study 1: Cardiac Procedures Service Line

In this case study, Care Pathways for cardiac care are used to drive a transformation towards value-based hospital. The case study provides the context for one example used throughout chapter 4, and described in section 4.1.4. It demonstrates how Cardiac Procedure services could be provisioned and delivered based on our work done in one hospital described in section 5.1. However, in this case study, we have used the hypothetical scenario of the creation of a Cardiac Procedures Service Line in order to improve the readability of the case study. The hypothetical scenario is partly based on actual work done at the hospital.

5.2.1 Overview of the Cardiac Procedures Service Line

We are going to use the following scenario in order to illustrate the case study:

- A large community hospital has built a Cardiac Catheterization Lab, and wants to create a Service Line for Cardiac Procedures
- An existing Cardiologist team is performing Cardiac Procedures at another hospital, and is going to start here.
- The hospital has negotiated new volumes with the Ministry of Health
- They have to decrease their case cost in order to meet the targets set by the Ministry of Health
- Their strategy is the following:
 - Design clinical workflows for Cardiac Procedures.
 - Redesign hospital organization in terms of a matrix rather than strictly departmental and create a new position of Director of Service Line.
 - Redesign IS for end-to-end support of the new Service Line.

As we step through the details of our COM platform in this chapter, we will use this scenario to illustrate COM models in section 5.2.3, corresponding UML/BPMN/DMN models in Section 5.2.4 and an example COSS prototype in section 5.2.5.

The typical cardiac patient journeys through the hospital are described in the figure below:

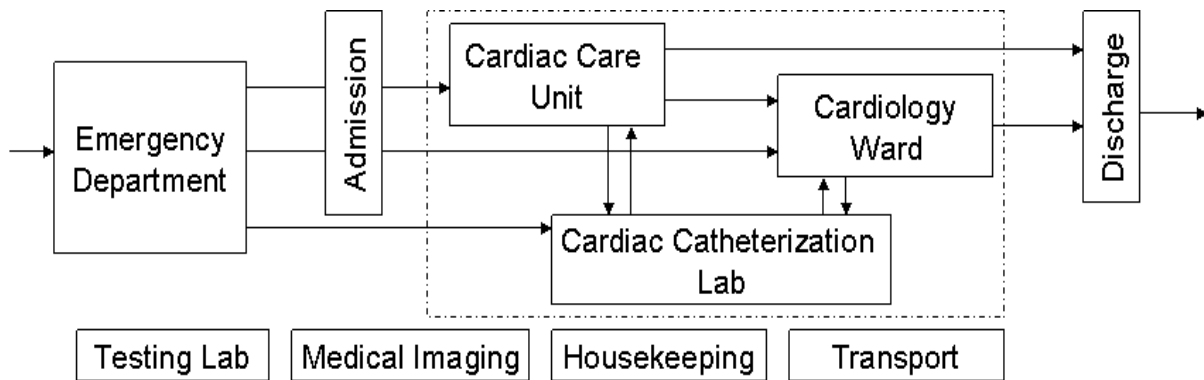


Figure 5-1 Patient Journeys

The main care pathways in the case study are: STEMI, NSTEMI Heart Attack, and Acute Coronary Syndrome (ACS).

The main Cardiac Procedures in the case study are: Angiography, Angioplasty, and Stenting.

The main operational processes in the case study are: Admissions; Discharge; Bed Management; procedure scheduling & booking; service provisioning; service delivery & monitoring.

The current system for Patient Flow Management (PFM) is paper-based. Clinical and operational performance data is collected manually, and is incomplete, and not timely. Decisions are made in ad hoc ways, manually, and are optimum for a specific clinical unit but not necessarily for overall patient flows across the entire continuum of care at the hospital.

Figure 5-2 shows the ACS care pathway, extracted from the Coronary Artery Disease QBP [QBP]:

Figure 6: Pathway for NSTEMI/UA

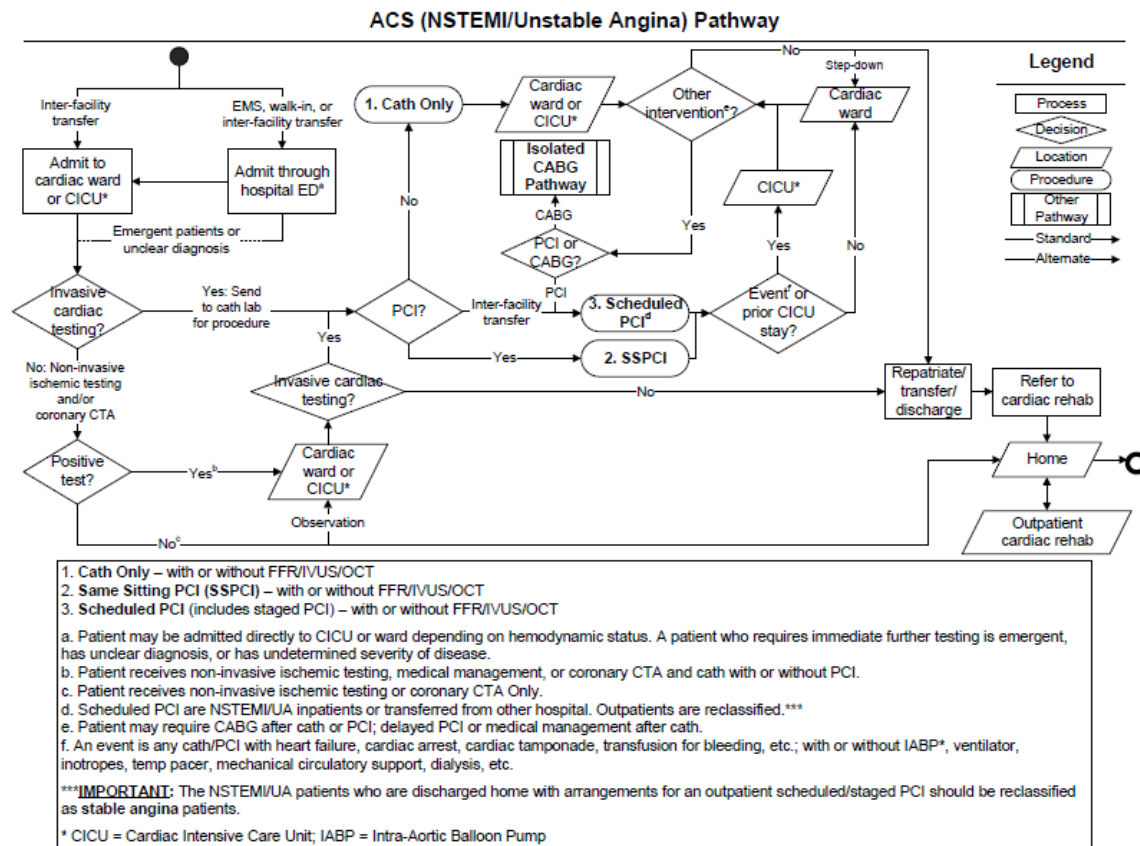


Figure 5-2 Acute Coronary Syndrome care pathway [QBP]

The Case Study follows the journey of a cohort of patients with Acute Coronary Syndrome (ACS):

- The patient presents to the Emergency Department and undergoes a medical assessment.
- They need an invasive cardiac testing (i.e an Angiogram) and are referred to the Cardiac Catheterization Lab
- The Angiogram is showing that an Angioplasty (also called PCI) is required soon. The Cardiac Cath Lab has capacity, and a Same Sitting PCI (SSPCI) is done. This means that the Angioplasty and Stenting are done while the catheter used for the Angiogram is still in place.
- Following the procedures, if there is a risk, the patient is sent to the Cardiac Intensive Care Unit (CICU) and then to the Cardiac Ward

- Otherwise, the patient is sent directly to the Cardiac Ward, and then is discharged from the hospital, with a referral to cardiac rehabilitation.

The goal is to leverage our COMP Tools and COM Models to validate how to provide information support for real-time access to operational performance information across the hospital, without burdening patients and clinicians, and then how to deliver decision-making support in real-time. Specifically, we wanted to explore the synergy between Real-Time Location Service (RTLS) and Business Process Management.

Some of the constraints are the following:

- The information system must NOT increase the cognitive burden on Physicians and Nurses [IOM2012]
- The information solution must be as automatic as possible
- Support is delivered to Clinicians at point-of-care

Our solution is to manage patient flows according to Care Pathways. PFM should be tailored to each specific Care Pathway: Automate and instrument Care Pathways in order to support Clinicians with task allocation, communication, checklists, and reminders. Then use RTLS to track patients and staff. Use location information and process information in order to automatically derive wait times and service times, without burdening the staff.

5.2.2 Case Study coverage of COM Functions Table

Table 5-1 below is the same as Table 4-2 COM Functions Table in a value-based hospital in section 4.2.1, with the highlighting of the COM Functions and decision-making levels covered by the case study.

Table 5-1 Case Study coverage of the COM Functions Table

COMF	Service Line Management	Demand Capacity Management	Performance Management	Quality of Care, Safety, and Risk Management	Supply Management	Accounting Management	Human Resources Management
Strategic (1-3 years)	Selection of Care Pathways and QBPs based on service mix and case mix	Service mix planning; Case mix planning; Capacity dimensioning; Workforce planning	Performance Management policies	QoC Policies; Culture of Safety; Accreditation	Supply Chain design; Materials Planning	Investment plan; Annual Budget	Organization structure; Workforce planning; Roles & responsibilities
Tactical (3-6 months)	Planning of care processes implementing customized Care Pathways and QBP for patient groups	Master Surgery Scheduling; Shift Scheduling; Scoping Ancillary Services	Performance Management planning; Historical Performance Analysis	QoC Reviews; Risk Management; Falls prevention; Infection Control policies	Supplier selection; Tenders; Procedure Card mgt	Budget tracking; Activity Based Costing; analysis	Hiring; Training; Change mgt; LEAN deployment
Operational - offline (1-4 weeks)	Care Plan for individual patient; Activity plan update	Appointment scheduling; Booking; Staffing; Admission Control	Operational Performance Forecasting (operational BI)	Infection Control; High-risk medication management	Stock purchasing; Non-Stock ordering	Billing; Cash-Flow analysis; Financial Control	Staffing; Workforce Mgt; Continuous improvements
Operational - online (real-time; daily)	Care Plan update in real-time; Activity management; Process Monitoring & Control	Capacity monitoring & control; Full-Capacity protocol; Staffing-to-Census; Real-Time Patient Flow Mgt; Housekeeping & Portering	Performance Monitoring & Control; Escalation management	Adverse Event monitoring & control; Escalation management	Inventory Control; Rush ordering; Unit inventory replenishing	Overtime tracking; Support for staffing-to-census	Sick time tracking; Support for staffing-to-census; Real-time staffing

The case study covers the functions Service Line Management, Demand Capacity Management and Performance Management in the Function View. It also focuses on supporting Operational decision-making. This is an example of how the COM Functions Table guides the design of the COSS to better support the hospital transformation; it enables to focus on specific features or capabilities while understanding how they relate to the bigger system.

5.2.3 COM Models

Figure 5-3 below is the same as Figure 4-3 COM Enterprise Architecture Diagram in section 4.1.1, with only the relevant parts shown.

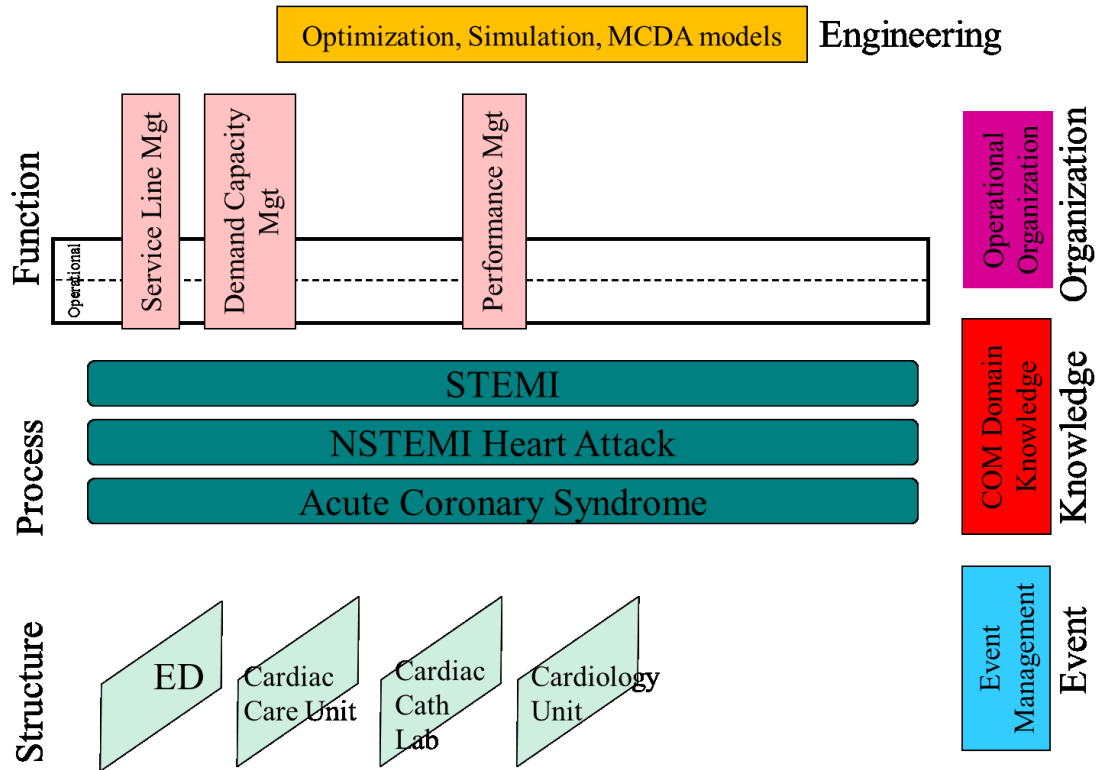


Figure 5-3 COM Enterprise Architecture Diagram for Cardiac Procedures Service Line

Figure 5-4 below shows the COM Models for the Cardiac Procedures service line in the case study.

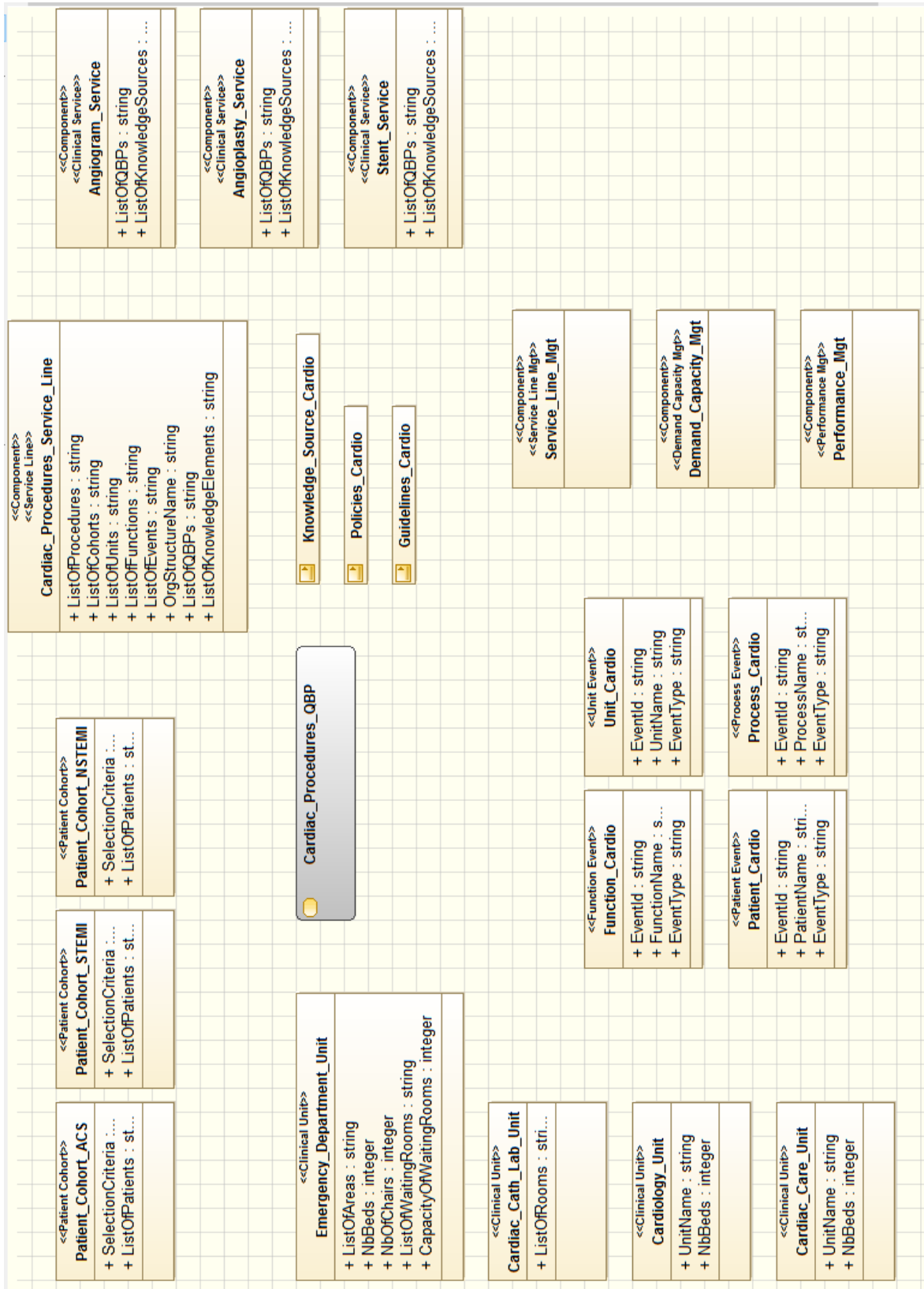


Figure 5-4 COM Models for Cardiac Procedures Service Line

5.2.4 UML/BPMN/DMN Models

- Figure 5-5 Participants and Components for Cardiac Procedures Service Line below shows the list of SOAML Participants and UML Components. This is a subset of the Participants and Components described in section 4.4. The same mapping between COM Models and SOAML Participants, described in section 4.4.1, is used. The Components composing the Participant remain the same.
- Figure 5-6 COOM1 for Cardiac Procedures Service Line shows the COOM1 information model. COOM2 and COOM3 remain the same as in section 4.4.2.
- Figure 5-7 BPMN Process for Cardiac Procedures Service Line - ACS (STEMI) shows a partial BPMN diagram for Acute Coronary Syndrome (STEMI).
- Figure 5-8 Examples of Rules and Event Rules for Cardiac Procedures Service Line shows examples of Decision Rules and Event Rules
- The weaving technique is the same as in section 4.4.5

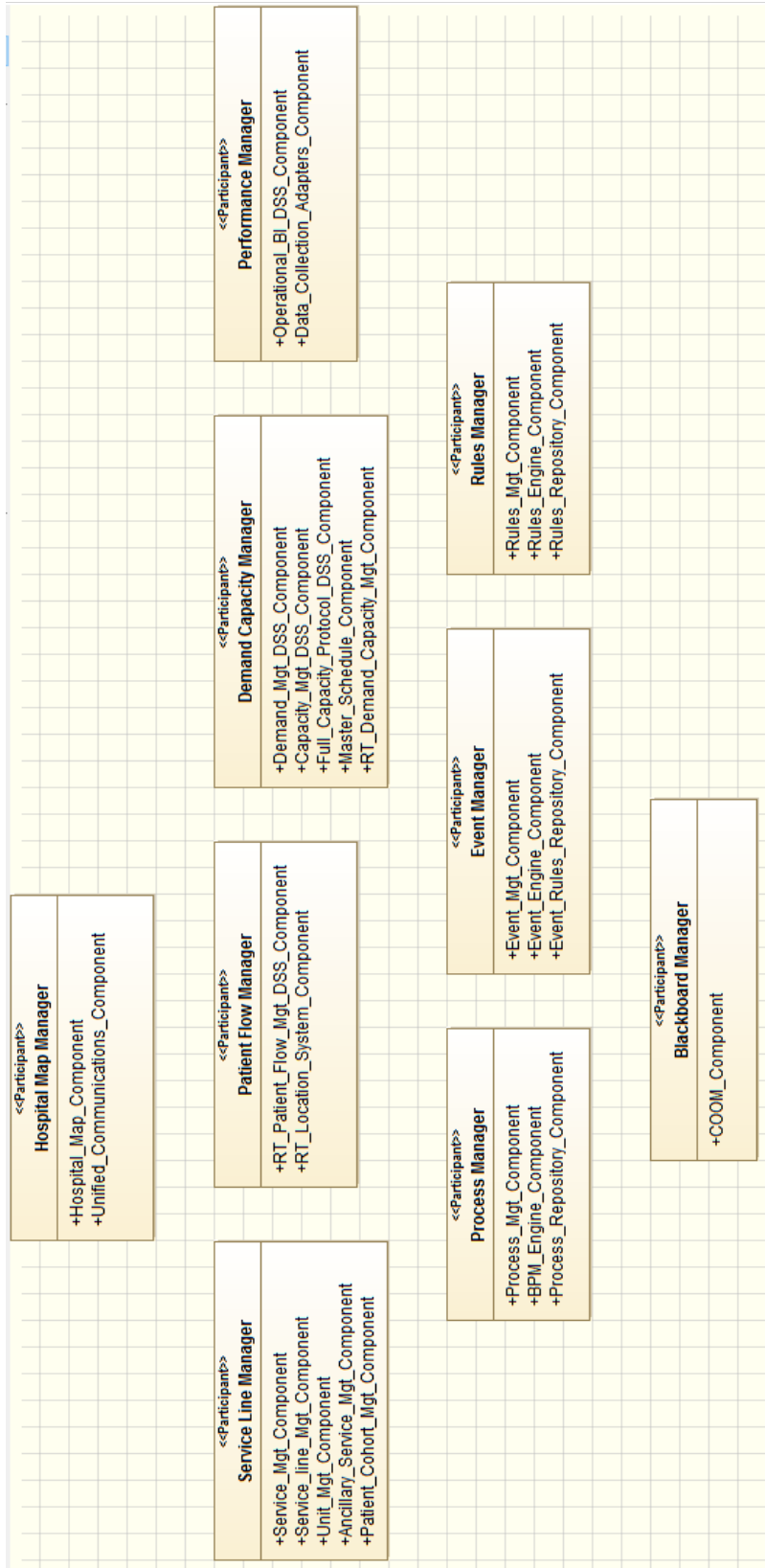


Figure 5-5 Participants and Components for Cardiac Procedures Service Line

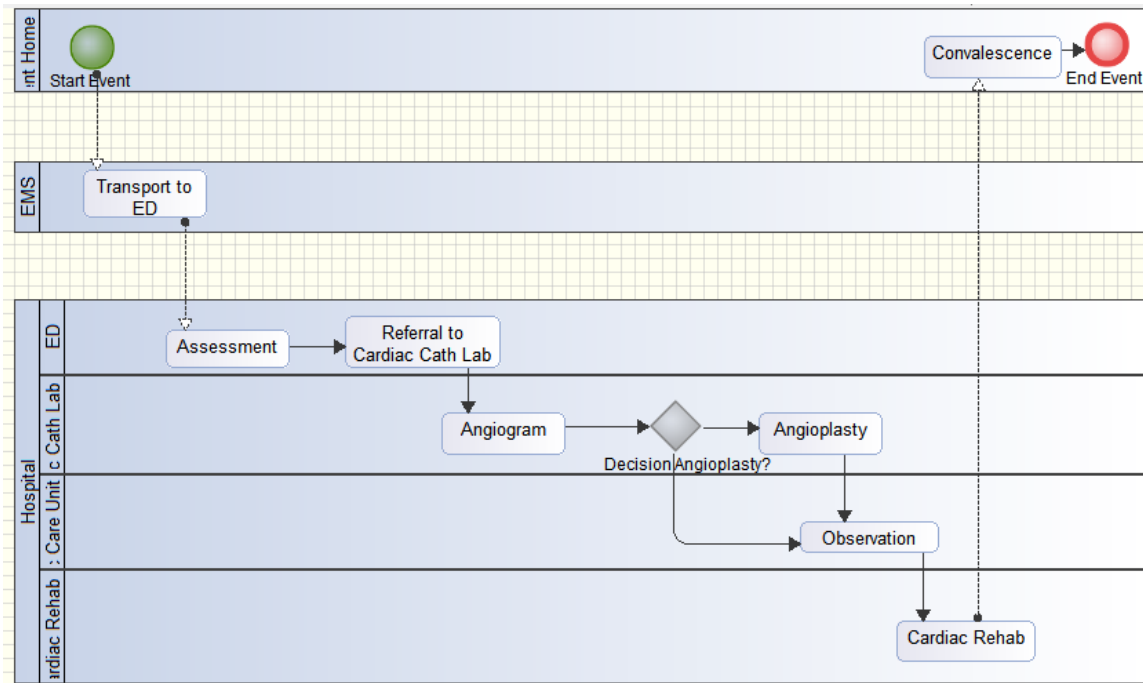


Figure 5-7 BPMN Process for Cardiac Procedures Service Line - ACS (STEMI)

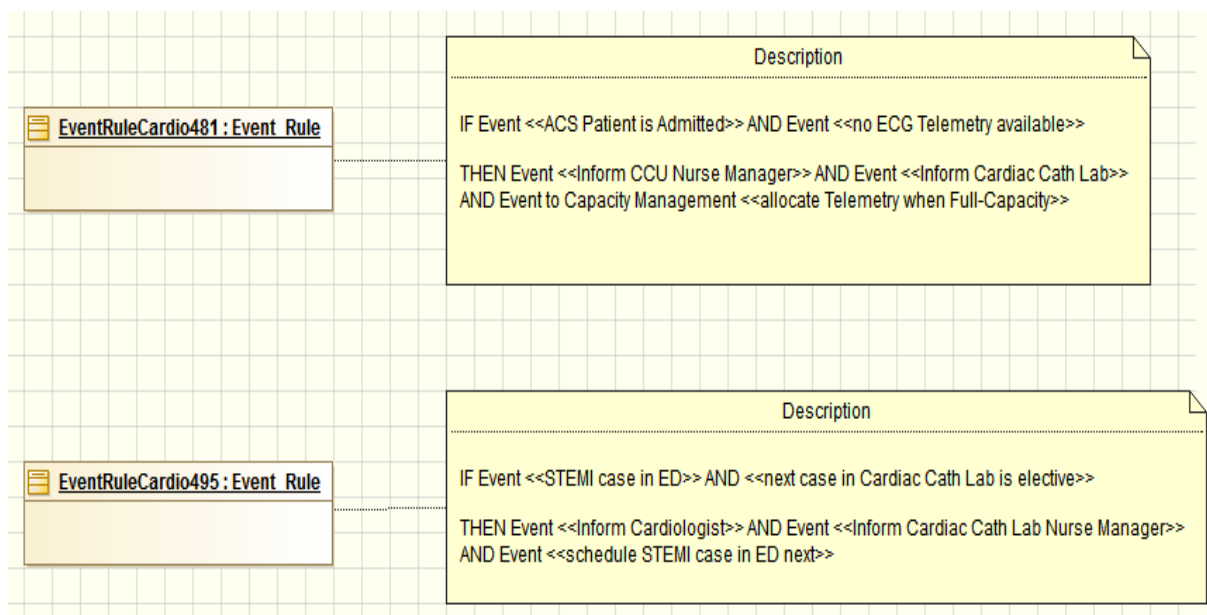
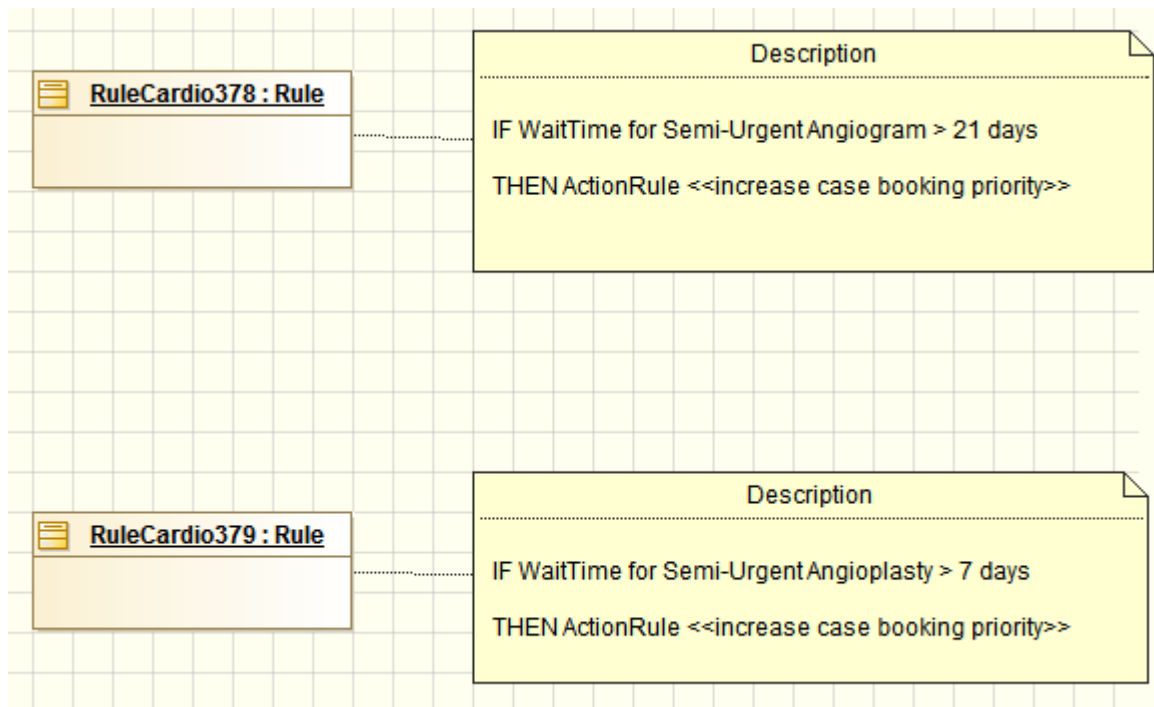


Figure 5-8 Examples of Rules and Event Rules for Cardiac Procedures Service Line

5.2.5 COSS Lab Prototype

The COSS lab prototype has been manually built (without COSBench) based on the COM Models and UML/BPMN/DMN Models. The COSS design was complete but the implementation was partial in the sense that we only implemented the code required to validate the major architecture mechanisms (described in section 5.5). Another objective with the COSS lab prototype was to improve and validate the COM and UML/BPMN/DMN Models.

Figure 5-9 below shows the COSS Architecture Diagram for the Cardiac Procedures Service Line. There is a 1-to-1 mapping between the COSS Modules and the Components listed in Figure 5-5 Participants and Components for Cardiac Procedures Service Line (plus Data Warehouse and HL7 Adapters to EMR).

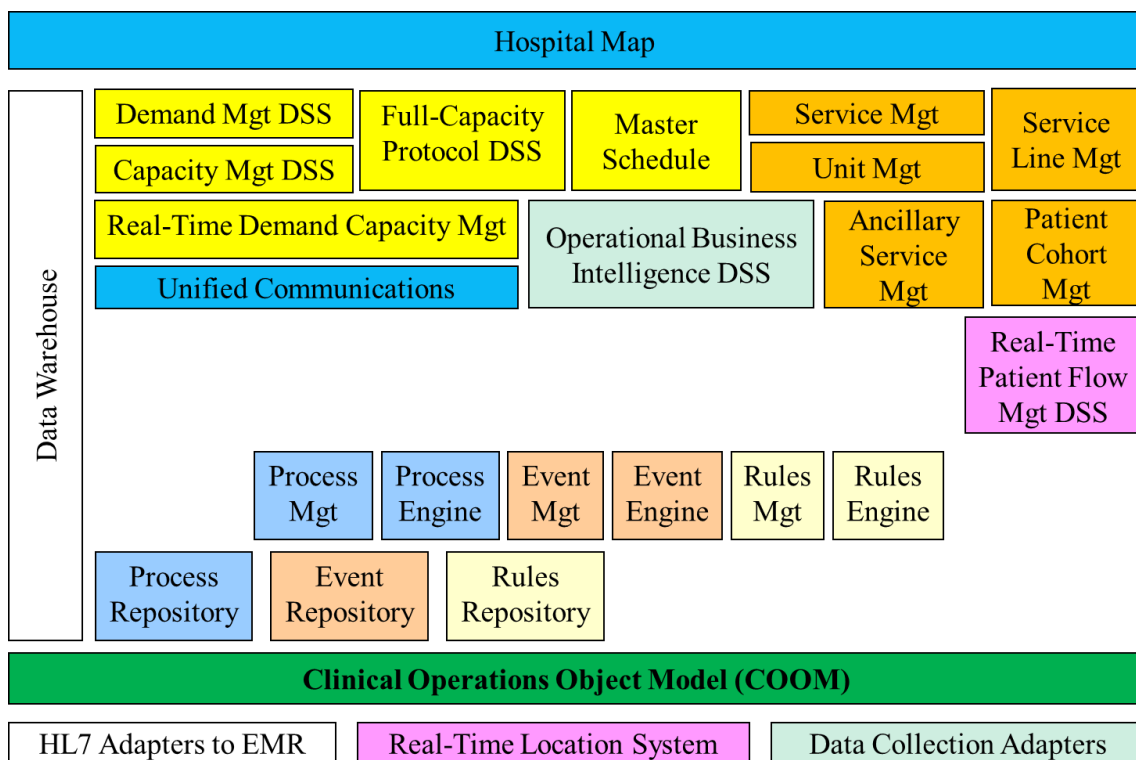


Figure 5-9 COSS Architecture Diagram for Cardiac Procedures Service Line

The COSS Lab Prototype has been built in 2 phases: A Phase 1 Prototype which has been demonstrated and assessed by the hospital staff, and a Phase 2 Prototype which has been used to validate the models.

Phase 1 Prototype:

Figure 5-10 describes a subset of the COSS Architecture in Figure 5-9 which has been designed and implemented first. Based on the COM Models of section 5.2.3 and the UML/BPMN Models of section 5.2.4, the Phase 1 Prototype focused on patient tracking with RTLS combined with care process management and event management. The work has been described in [Tchemeube2013]. The Phase 1 Prototype has been demonstrated to the hospital staff and an assessment survey has been collected, as described in section 5.2.6.

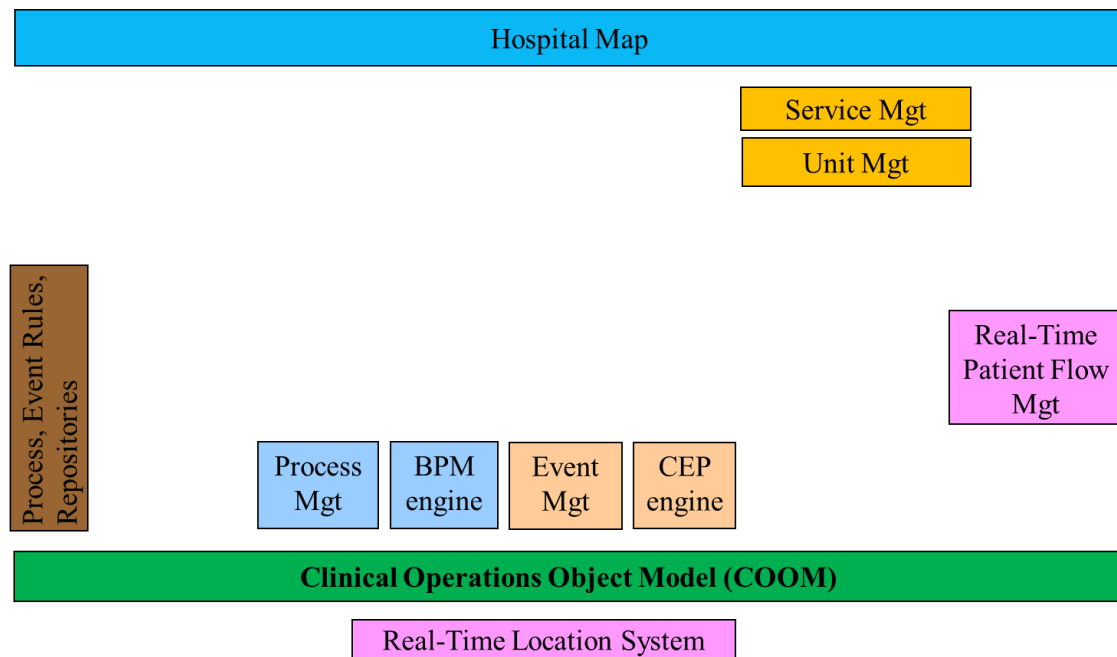


Figure 5-10 COSS Architecture Diagram for Phase 1 Prototype

Phase 2 Prototype:

The Phase 2 Prototype designed the entire COSS Architecture in Figure 5-9 COSS Architecture Diagram for Cardiac Procedures Service Line, and partially implemented the COSS Modules in order to be able to run the 2 Use Case scenarios described below.

Use Case 1:

The Use Case 1 follows the journey of a cardiac patient with Acute Coronary Syndrome when he presents at 10:00 to the Emergency Department, is assessed, waits for blood test results, is referred to the Cardiac Cath Lab, undergoes an Angiogram and Angioplasty, is cohorted in an occupied double-bed room in the Cardiology Unit, recovers, and then is discharged from the hospital the following day.

Here is the detailed sequence:

- At 07:30, the Flow Coordinator Nurse sees from the Real-Time Demand Capacity Mgt module that a shortage of beds in the Cardiology Unit is forecast during the afternoon, based on the known, planned discharges and admissions of the day.
- At 08:00, the Flow Coordinator and the Cardiology Nurse Manager communicate in a videoconference using the Unified Communications module about the forecasts of the Real-Time Demand Capacity Mgt module. They discuss an action plan to free beds.
- At 10:00, the Patient presents at the ED with chest pain. He is equipped with an RFID wrist-tag in order to be tracked automatically. He sees the Emergency Physician at 10:20. A blood test is requested.
- The Real-Time Patient Flow Mgt DSS and the Operational Business Intelligence DSS collaborate using the COOM1 blackboard in order to automatically measure the patient wait times in the ED, including the wait for blood test results.
- At 10:50, with all test results available and automatically downloaded on her tablet by the Ancillary Service Mgt module, the Emergency Physician comes back to reassess the Patient, and confirms a diagnosis of ACS (NSTEMI). She refers the Patient to the Cardiac Cath Lab at 10:55.
- At 11:00, after having analyzed the bed occupancy throughout the hospital, the Real-Time Patient Flow Mgt DSS, the Operational Business Intelligence DSS, and the Full-Capacity Protocol DSS, working together using the COOM1 blackboard, provide a recommendation to the Flow Coordinator to activate the Full-Capacity Protocol in the hospital. This is done at 11:15.

- At 11:30, the Cardiologist and the Cardiac Cath Lab Nurse Manager book the patient for the 13:30 slot in the Cardiac Cath Lab, based on the schedule and case priorities of the day.
- At 11:45, the Patient is transferred from the ED to the Cardiac Cath Lab. The Service Line Mgt and Service Mgt modules had sent notifications to Portering for the transport of the Patient.
- At 13:30, the Patient undergoes an Angiogram followed by an Angioplasty.
- At 14:25, the Patient is moved to the post-procedure area, and waits for a bed in the Cardiology Unit.
- At 17:00, the Real-Time Patient Flow Mgt DSS, the Operational Business Intelligence DSS, and the Full-Capacity Protocol DSS, working together using the COOM1 blackboard, provide a recommendation to the Flow Coordinator and to the Cardiology Unit Nurse Manager to cohort the Patient in an already occupied double-bed room because of the Full-Capacity Protocol still active. They both communicate via videoconference using the Unified Communications module, and agree to cohort the patient in room 328.
- At 17:20, the bedside Nurse prepares the double-bed room 328 to receive a 3rd patient
- At 17:45, the Patient is transferred from the Cardiac Cath Lab post-procedure area to the Cardiology Unit. The Service Line Mgt and Service Mgt modules had sent notifications to Portering for the transport of the Patient.
- The following day at 10:00, the Patient is discharged.
- During this entire Use Case 1 scenario, the Service Line Mgt and Patient Cohort Mgt modules have kept statistics, and presented reports to the Nurses, Physicians, Service Line Nurse Coordinator, and Service Line Director about the service line performance, the status of service line Patient Cohorts, and have sent notifications about any major event impacting the service line and patient cohorts.

Beyond the Phase 1 COSS modules, the Use Case 1 exercises the following COSS Modules:

- Real-Time Patient Flow Mgt DSS
- Operational Business Intelligence DSS
- Rules Mgt, Rules Engine, Rules Repository
- Service Line Mgt, Patient Cohort Mgt, Ancillary Service Mgt
- Real-Time Demand Capacity Mgt
- Full-Capacity Protocol DSS
- Unified Communications
- COOM1

This Use Case 1 has enabled us to understand, research, and design the Real-Time Patient Flow Mgt DSS, the Operational Business Intelligence DSS, and the Full-Capacity Protocol DSS, working together using the COOM1 blackboard, as described in section 4.6. For Use case 1, the DSS were simulated with scripted requests/responses/events.

Use Case 2:

The Use Case 2 scenario is about a cardiac patient with ACS who is scheduled to undergo an Angioplasty. As opposed to Use Case 1, this is an elective case which has to be scheduled.

Here is the detailed sequence:

- On Monday, Feb 1st, Cardiologist X and Patient A agreed on an elective Angioplasty, to take place in the Cardiac Cath Lab of the hospital.
- According to the ACS QBP, the recommended wait time for an Elective Angioplasty in Ontario is 28 days. However, the hospital has a policy to keep the wait time below 21 days.
- The Cardiologist office is tentatively scheduling the Patient for Monday Feb 22nd.
- Although there is a slot available, based on historical data, the Demand Mgt DSS is recommending to keep the slot open for any emergency Angioplasty. It is now

working with the Capacity Mgt DSS, using the COOM2 blackboard, and the Master Schedule, in order to find an optimal slot earlier.

- The Capacity Mgt DSS knows the Patient is a high-risk, and knows that in this case, the Cardiologist would prefer to operate on him early in the day.
- The Capacity Mgt DSS, using the Master Schedule, and the Demand Mgt DSS looking together at the options available on the COOM2 blackboard, finally agree on Thursday Feb 18th at 08:30.

The Use Case 2 exercises the following COSS Modules:

- Demand Mgt DSS
- Capacity Mgt DSS
- Master Schedule
- Rules Mgt, Rules Engine, Rules Repository
- COOM2

This Use Case 2 has enabled us to understand, research, and design the Capacity Mgt DSS, using the Master Schedule, and the Demand Mgt DSS, working together using the COOM2 blackboard, as described in section 4.6. For Use case 2, the DSS were simulated with scripted requests/responses/events.

5.2.6 Assessment Survey for the Phase 1 Prototype

The COSS lab prototype that resulted from our enterprise architecture was demonstrated to Osler for validation. A survey (Figure 5-11 below) assessed the perceived value of the lab prototype by Executives, clinicians, and IT staff.

- Context
 - An initial demo was given to Osler CIO at uOttawa in July. Feedback has been collected about possible improvements.

- 13 demos were given to targeted groups during the week of Oct 22nd
- Continuous demos were given on Oct 29th, during the Patient Safety Week
- Outcomes
 - More than 100 Osler people attended
 - 65 survey forms were collected
 - Groups: SIPS LT, SLT, Corporate Registration, PMO, Quality & Risk Mgt, Access & Flow Mgt, Cardiology, DI, ED, Mental Health, OBS, Surgery, Pharmacy, Clinical Informatics Analysts, BI, IT Infrastructure

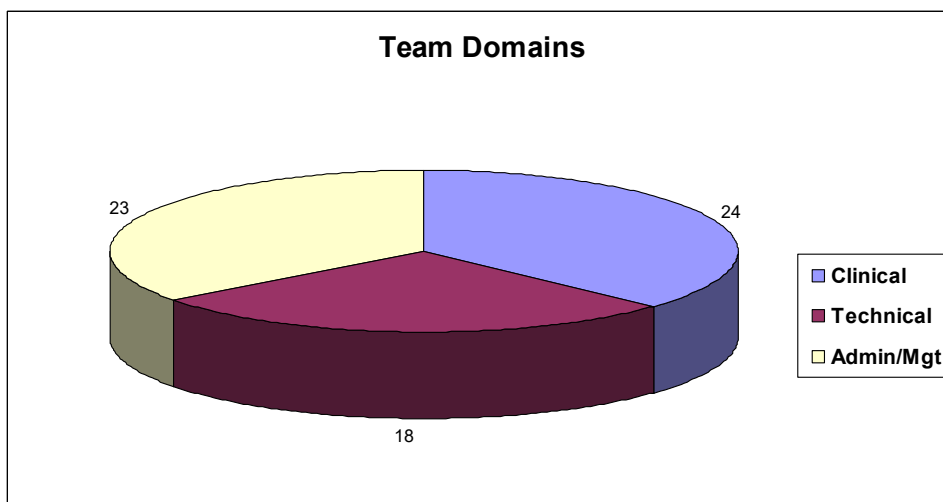


Figure 5-11 Team Domains

The survey questions were:

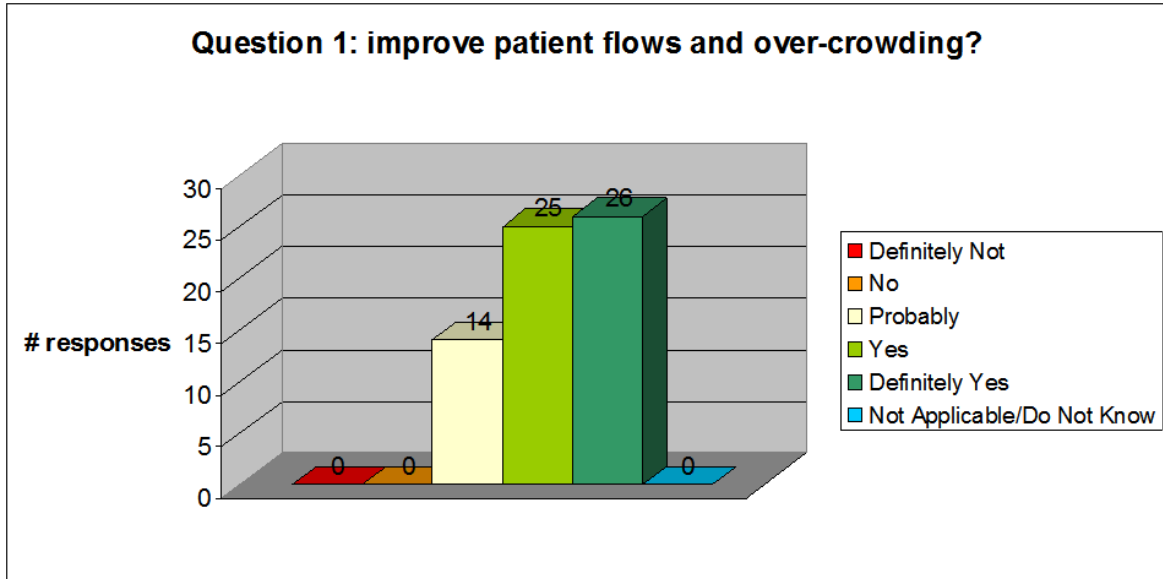
Q1: This technology and approach would improve patient flows and over-crowding (Definitely Not, No, Probably, Yes, Definitely Yes)
Q2: This technology and approach would be better than what currently exists to manage patient flows (Definitely Not, No, Probably, Yes, Definitely Yes)
Q3: This technology and approach would increase patient safety and quality of care (Definitely Not, No, Probably, Yes, Definitely Yes)
Q4: This technology and approach would improve the patient experience (Definitely Not, No, Probably, Yes, Definitely Yes)

• Q5: This technology and approach would be compatible with the values and needs of Osler Clinicians (Definitely Not, No, Probably, Yes, Definitely Yes)
• Q6: This technology and approach would improve the efficiency and efficacy of Osler Clinicians (Definitely Not, No, Probably, Yes, Definitely Yes)
• Q7: This technology and approach would ideally be adopted at Osler in (1, 2, 3, 5 years, Never)

Methodology:

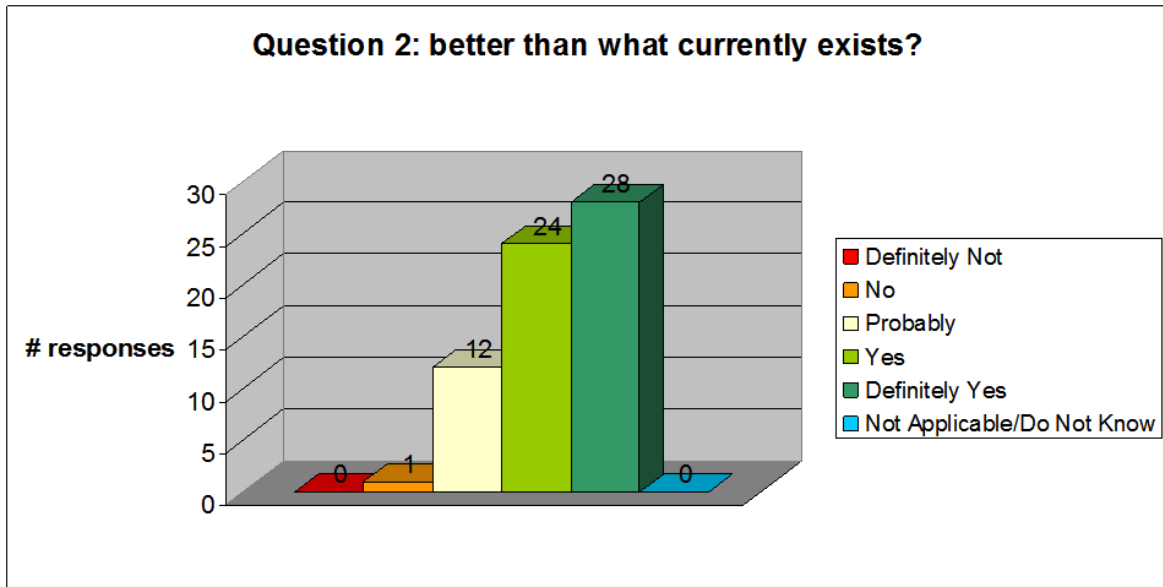
- Questions Q1 and Q2 assess whether, in Osler's staff perception, we had met their expectations to demonstrate a new system capable of addressing the patient flow problem, and whether it is better than what currently exists.
- Questions Q3 and Q4 assess whether, in Osler's staff perception, the system would positively impact what matters most to the patient: safety, quality of care, patient experience while in hospital
- Questions Q5 and Q6 assess the adoptability of the system by the Osler Clinicians specifically: do they feel that the approach of tracking people is compatible with their values and needs, and whether they perceive the technology to be helping them personally.
- Question Q7 is trying to assess the relative congruence of the answers to the previous questions with when they believe the technology should ideally be deployed at Osler. With the fast pace at which technology is progressing, an answer of 5 + years means that it's unlikely that it'll be deployed.

The Survey Results are:



- 79% Yes/Definitely Yes
- 21% Probably

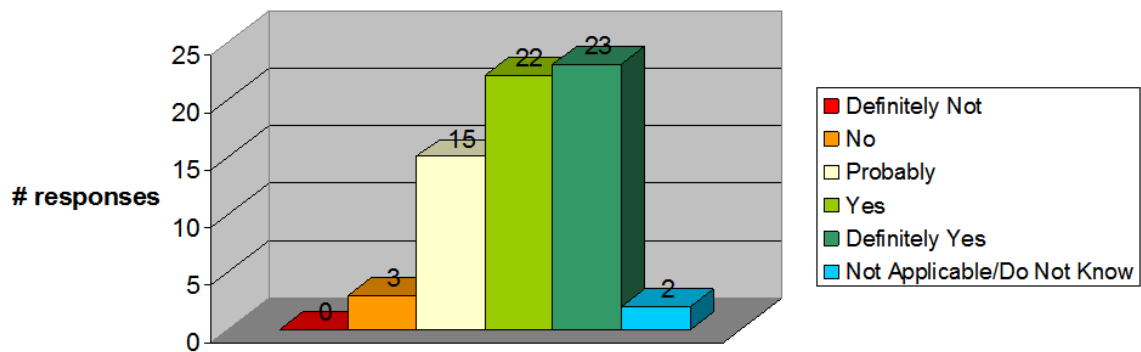
Figure 5-12 Question 1



- 80% Yes/Definitely Yes
- 18% Probably
- 2% No

Figure 5-13 Question 2

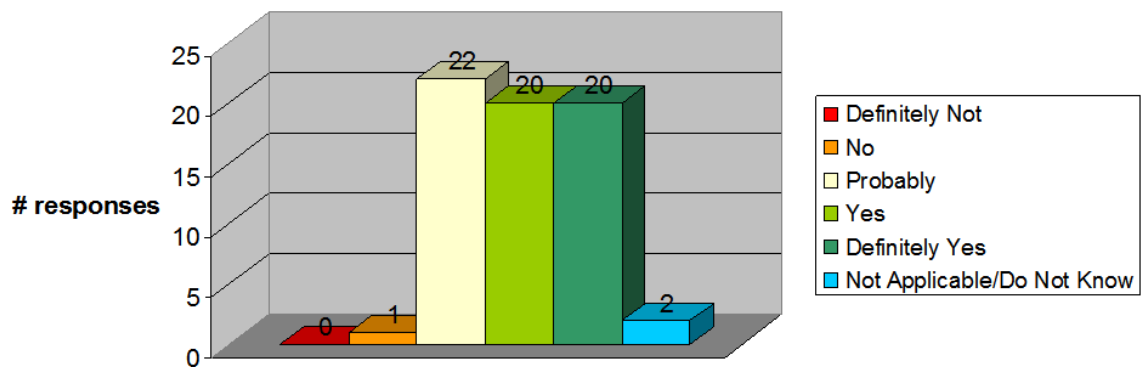
Question 3: increase patient safety and quality of care?



- 69% Yes/Definitely Yes
- 23% Probably
- 5% No
- 3% NA/DNK

Figure 5-14 Question 3

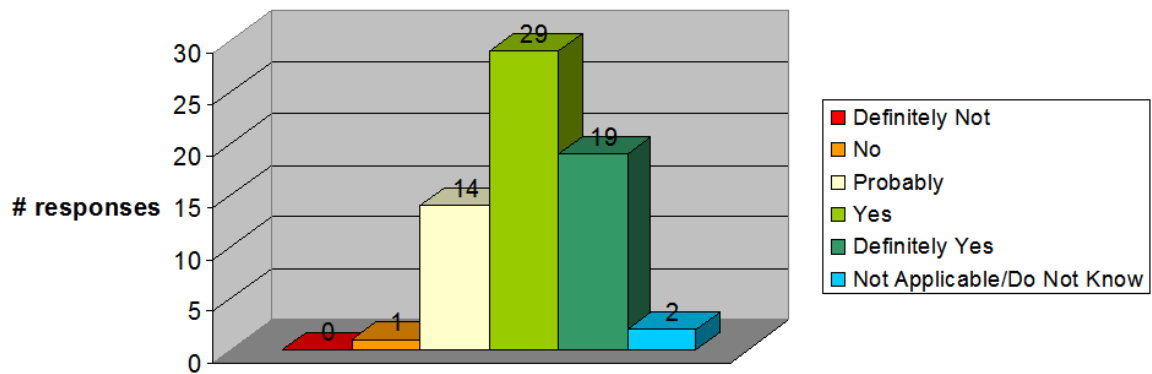
Question 4: improve the patient experience?



- 61% Yes/Definitely Yes
- 34% Probably
- 2% No
- 3% NA/DNK

Figure 5-15 Question 4

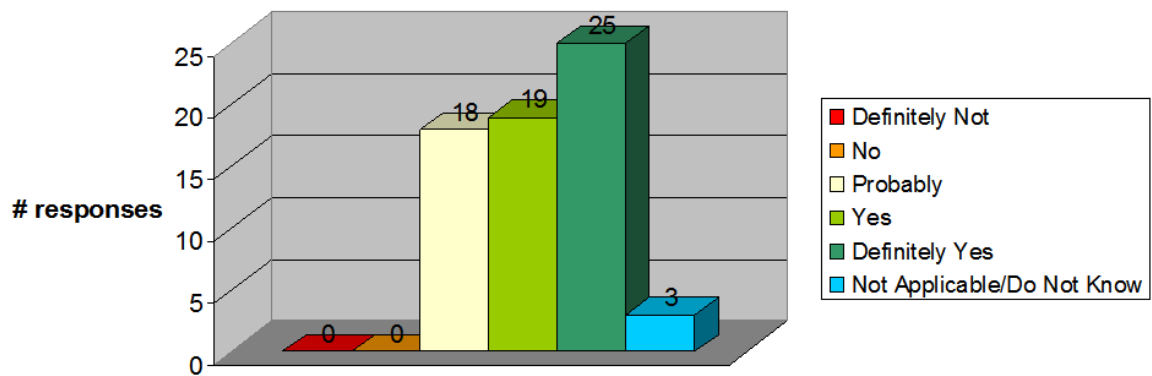
Question 5: compatible with values/needs of Osler Clinicians?



- 74% Yes/Definitely Yes
- 21% Probably
- 2% No
- 3% NA/DNK

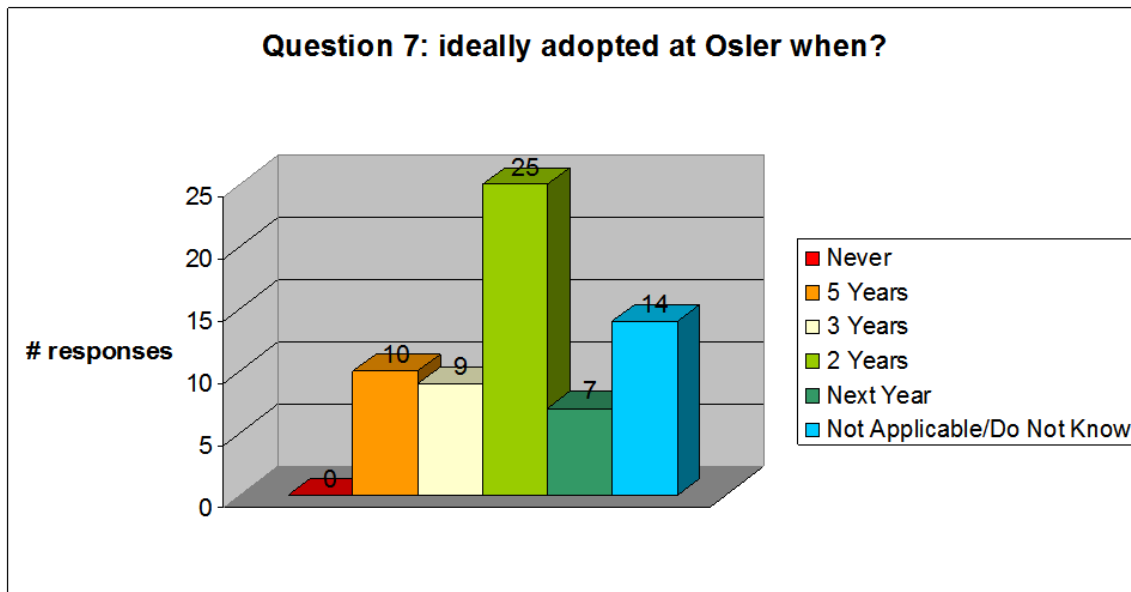
Figure 5-16 Question 5

Question 6: improve efficiency/efficacy of Osler Clinicians?



- 68% Yes/Definitely Yes
- 27% Probably
- 5% NA/DNK

Figure 5-17 Question 6



- 50% 1 – 2 years
- 29% 3 – 5 years
- 21% NA/DNK

Figure 5-18 Question 7

- The overall positive perception of the system is reinforced with the opinion of 50% of the surveyed staff that the system should ideally be deployed within 2 years, and another 14% thinking that it should be deployed within 3 years. 21% can't formulate an opinion.
- A feedback about the technology used is that the RFID tag is too big, and would not do for Pediatrics.

5.2.7 Results

The COM Models and UML/BPMN/DMN Models for the Cardiac Procedures Service Line have been built. They have been discussed with Cardiologists, Cardiology Nurses, and with Analysts, in several iterations, when we were doing the value stream mapping of these clinical services. The Physicians and Nurses found the COM Models very useful in helping them formalize and document their practice.

The Assessment Survey has shown that the Phase 1 Prototype was well received by the hospital staff.

The Use Case 1 and 2 have exercised all the COSS Modules of the Phase 2 Prototype, and shown its technical feasibility. It has to be noted that the DSS were simulated with scripted requests/responses/events.

5.3 Case Study 2: Joint Replacement Service Line

This Case Study provides the context for one example used throughout chapter 4. It demonstrates how Hip & Knee Replacement services could be provisioned and delivered based on our work done in the 2 hospitals described in section 5.1. However, in this case study, we have used the hypothetical scenario of the creation of a Joint Replacement Service Line in order to improve its readability. The hypothetical scenario combines data from both hospitals into a hypothetical hospital.

5.3.1 Overview of Joint Replacement Service Line

We are going to use the following scenario in order to illustrate the case study:

- A large community hospital wants to create a Service Line for Joint Replacement
- An existing Orthopedic Surgery team is already performing Hip & Knee Replacement surgeries, but at low volumes.
- The hospital has negotiated new volumes with the Ministry of Health
- They have to decrease their case cost in order to meet the targets set by the Ministry of Health
- Their strategy is the following:
 - Redesign clinical workflows for Hip & Knee Replacement surgery.
 - Redesign hospital organization in terms of a matrix rather than strictly departmental and create new positions of Service Line Director and Service Line Nursing Coordinator.

- Redesign IS for end-to-end support of the new Service Line.

The Hip & Knee Replacement QBP is presented below [QBP]:

Primary Hip and Knee Replacement Episode of Care Model

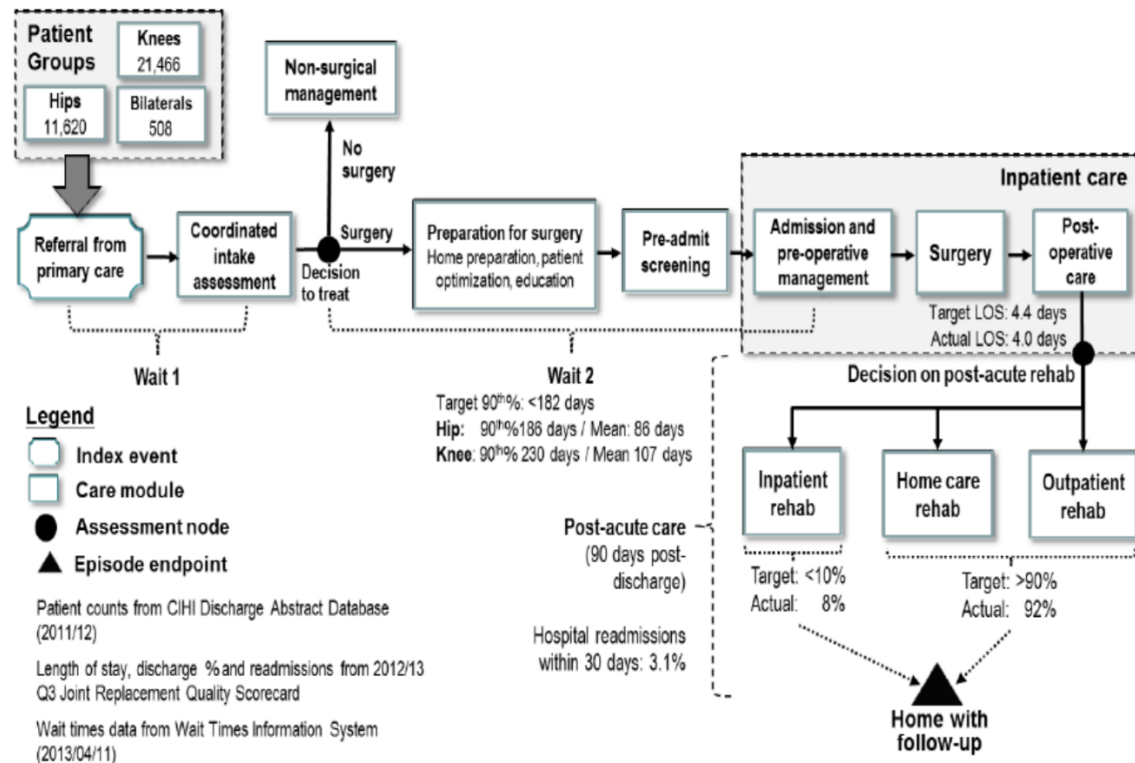


Figure 5-19 Hip & Knee Replacement QBP [QBP]

There are 2 cohorts of patients: Hip Replacement cohort, and Knee Replacement cohort. They get referred by their Primary Care Physician to a Central Intake Assessment center who, based on wait times and patient preferences, allocates the Orthopedic Surgeon. Following the consultation. If the decision is indeed to operate, the patient is referred to a Clinic where the preparation for surgery is made. On the day of surgery, the patient is screened, admitted, and undergoes pre-operative preparation. Following the surgery, the patient is transferred to the Surgery Unit, and is normally discharged 2 or 3 days later with order for physiotherapy at a Rehab Clinic.

5.3.2 Case Study coverage of COM Functions Table

Table 5-2 below is the same as Table 4-2 COM Functions Table in a value-based hospital in section 4.2.1, with the highlighting of the COM Functions and decision-making levels covered by the case study. The case study covers all the functions and all the levels of decision-making.

Table 5-2 Case Study coverage of COM Functions Table

COMF	Service Line Management	Demand Capacity Management	Performance Management	Quality of Care, Safety, and Risk Management	Supply Management	Accounting Management	Human Resources Management
Strategic (1-3 years)	Selection of Care Pathways and QBP based on service mix and case mix	Service mix planning; Case mix planning; Capacity dimensioning; Workforce planning	Performance Management policies	QoC Policies; Culture of Safety; Accreditation	Supply Chain design; Materials Planning	Investment plan; Annual Budget	Organization structure; Workforce planning; Roles & responsibilities
Tactical (3-6 months)	Planning of care processes implementing customized Care Pathways and QBP for patient groups	Master Surgery Scheduling; Shift Scheduling; Scoping Ancillary Services	Performance Management planning; Historical Performance Analysis	QoC Reviews; Risk Management; Falls prevention; Infection Control policies	Supplier selection; Tenders; Procedure Card mgt	Budget tracking; Activity Based Costing; analysis	Hiring; Training; Change mgt; LEAN deployment
Operational - offline (1-4 weeks)	Care Plan for individual patient; Activity plan update	Appointment scheduling; Booking; Staffing; Admission Control	Operational Performance Forecasting (operational BI)	Infection Control; High-risk medication management	Stock purchasing; Non-Stock ordering	Billing; Cash-Flow analysis; Financial Control	Staffing; Workforce Mgt; Continuous improvements
Operational - online (real-time; daily)	Care Plan update in real-time; Activity management; Process Monitoring & Control	Capacity monitoring & control; Full-Capacity protocol; Staffing-to-Census; Real-Time Patient Flow Mgt; Housekeeping & Porterage	Performance Monitoring & Control; Escalation management	Adverse Event monitoring & control; Escalation management	Inventory Control; Rush ordering; Unit inventory replenishing	Overtime tracking; Support for staffing-to-census	Sick time tracking; Support for staffing-to-census; Real-time staffing

5.3.3 COM Models

Figure 5-20 below is the same as Figure 4-3 COM Enterprise Architecture Diagram in section 4.1.1, with only the relevant parts shown.

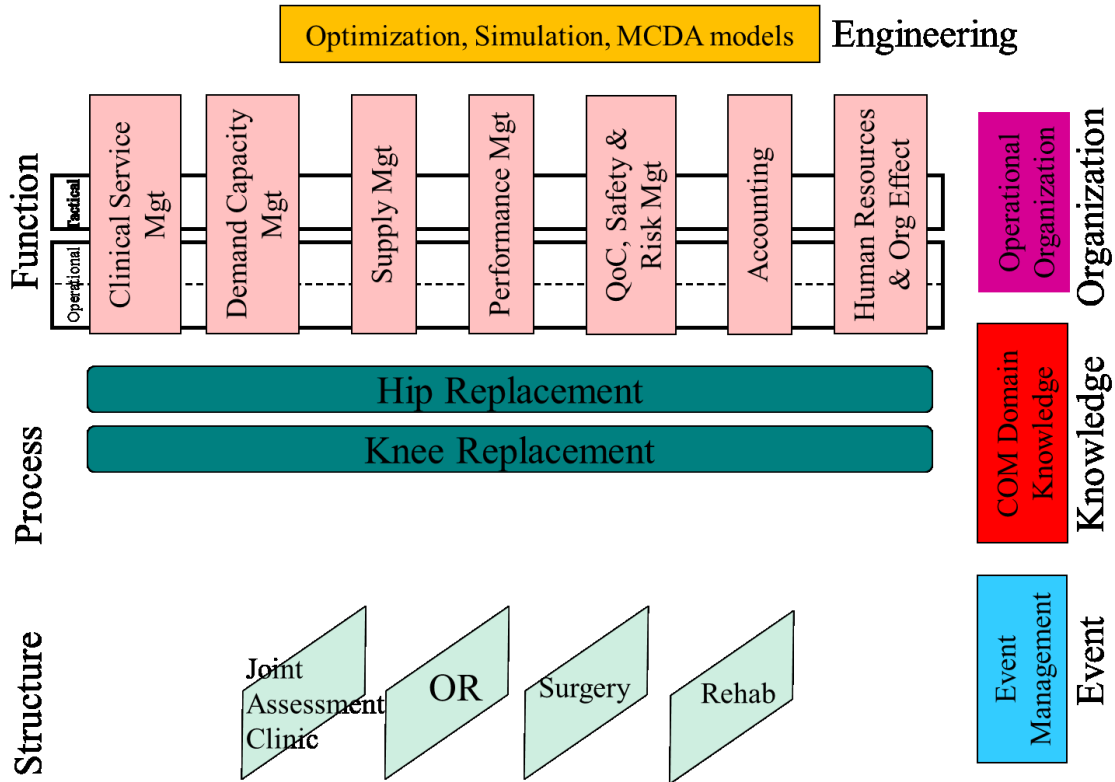


Figure 5-20 COM Enterprise Architecture Diagram for Joint Replacement Service Line

Figure 5-21 below shows the COM Models for the Joint Replacement service line in the case study. This is exactly the same as Figure 4-12 COM Models for Joint Replacement Service Line in section 4.3.2. We duplicated it here in order to visualize the alignment of the COM Models on the COM Enterprise Architecture Diagram and the COM Functions Table.

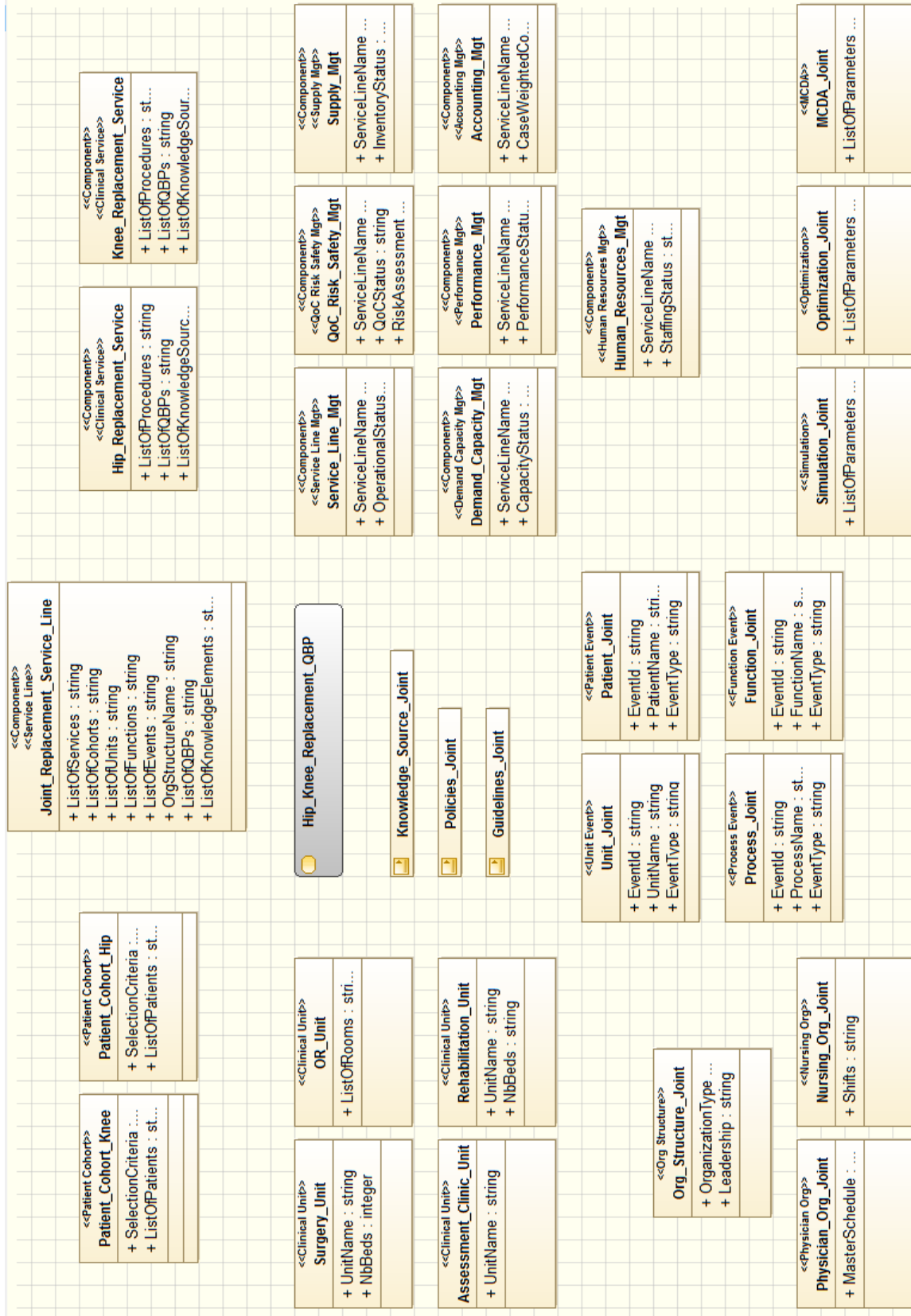


Figure 5-21 COM Models for Joint Replacement Service Line

5.3.4 UML/BPMN/DMN Models

- The list of SOAML Participants (plus the Hospital Map Manager and the Blackboard Manager) and UML Components is the same as described in Figure 4-23 SOAML Participants and UML Components in section 4.4.1. The same mapping between COM Models and SOAML Participants, described in section 4.4.1, is used. The 39 Components composing the Participants remain the same.
- The COOM1 information model for Joint Replacement is the same as Figure 4-33 Example of COOM1 for Joint Replacement in section 4.4.2. COOM2 and COOM3 remain the same as in section 4.4.2.
- The partial BPMN diagram for Joint Replacement is the same as Figure 4-34 BPMN Process for Hip & Knee Replacement QBP in section 4.4.3
- Figure 5-22 below shows examples of Decision Rules and Event Rules for Joint Replacement service line
- The weaving technique is the same as in section 4.4.5

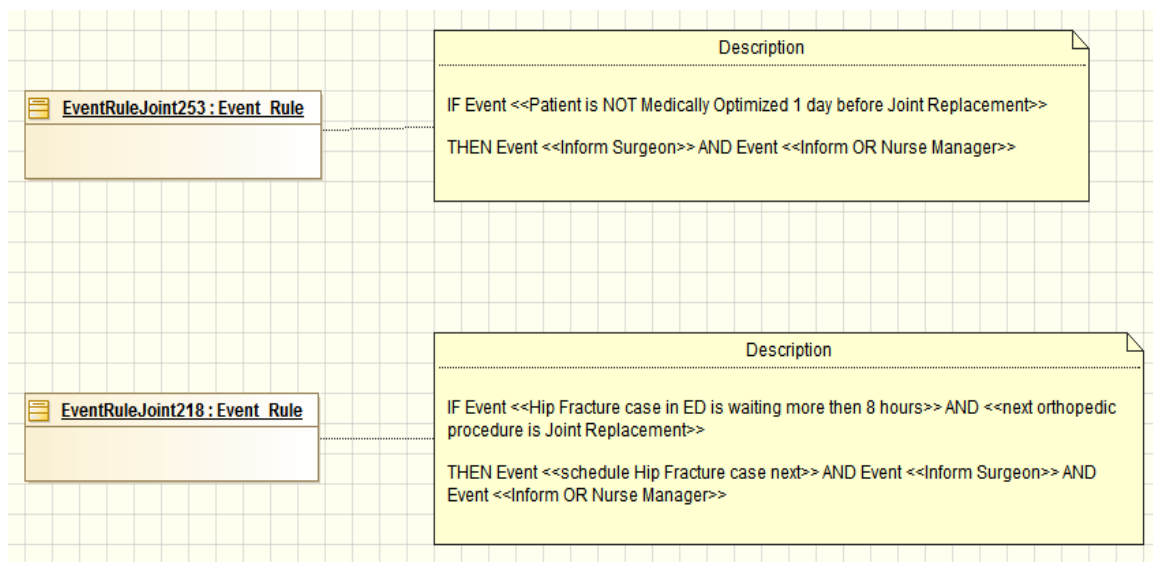
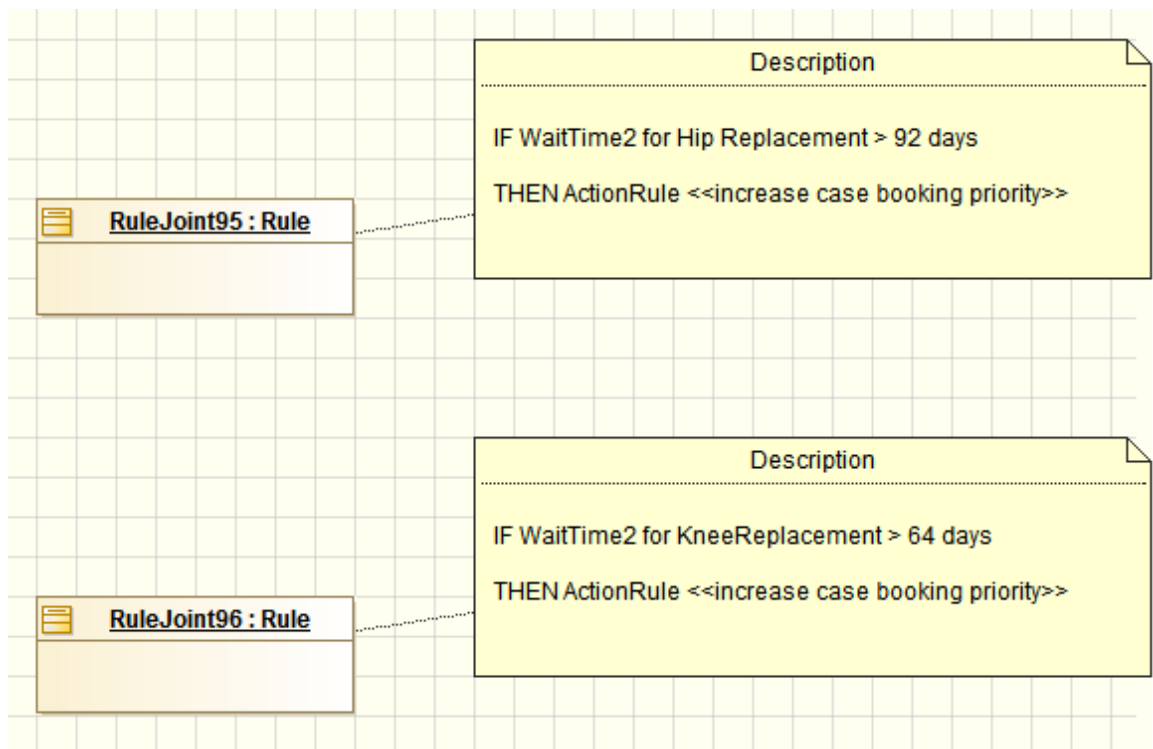


Figure 5-22 Examples of Rules and Event Rules for Joint Replacement Service Line

5.3.5 COSS Lab Prototype

The COSS lab prototype has been manually built (without COSBench). The COSS design was complete but the implementation was partial in the sense that we only implemented the code required to validate the major architecture mechanisms per section 5.5. Another objective with the COSS lab prototype was to improve and validate the COM and UML/BPMN/DMN Models.

Figure 5-23 below shows the COSS Architecture Diagram for the Joint Replacement Service Line, and is the same as Figure 4-40 COSS Architecture Diagram of section 4-6.1. We duplicated it here in order to visualize the alignment of the COSS Architecture Diagram with the COM Models, the COM Enterprise Architecture Diagram, and the COM Functions Table. This also facilitates the understanding of the Uses Cases below.

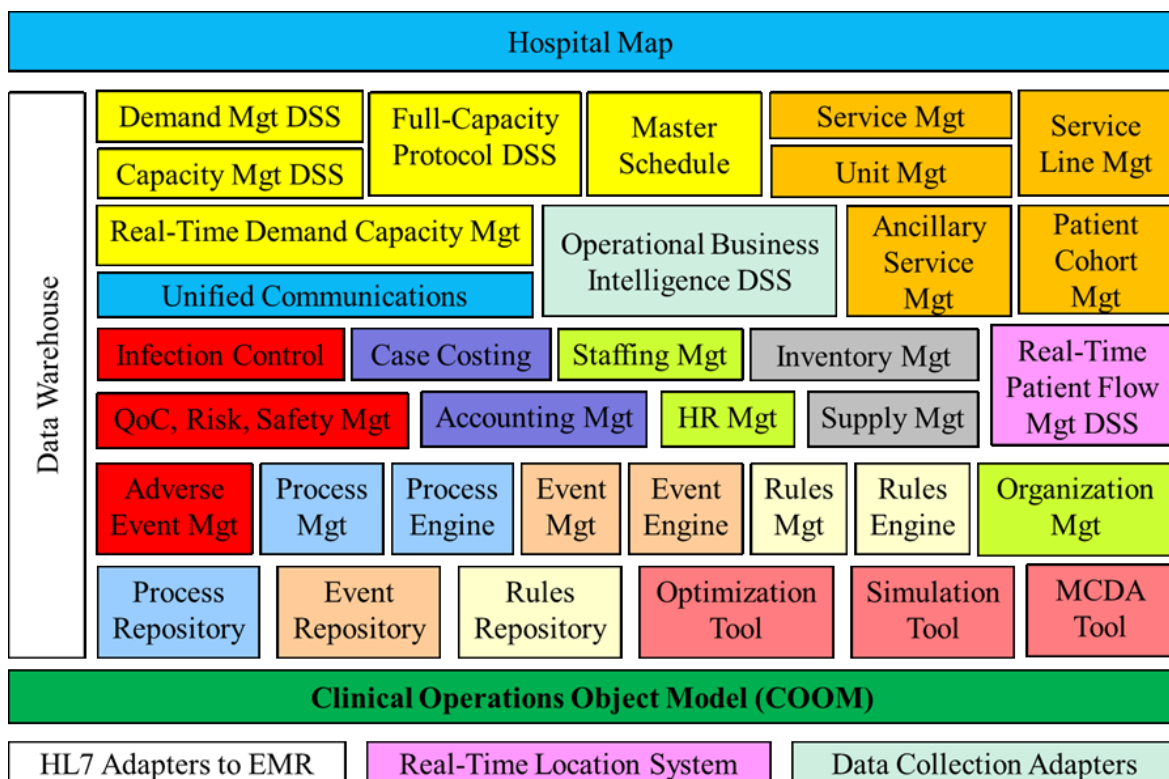


Figure 5-23 COSS Architecture Diagram for Joint Replacement Service Line

Overview of Use Case Scenarios for Joint Replacement

There are 3 Use Case scenarios in the case study:

- Creation and Design of the Joint Replacement Service Line (Strategic and Tactical decision-making)
- The Hip & Knee Replacement Patient is being booked by Surgeon's office: this is the service provisioning (Operational Off-line decision-making)
- The Hip & Knee Replacement Patient arrives in OR for the Same-Day Admission: this is the service delivery (Operational On-line decision-making)

Use case 3: Service Line Creation and Design

The hospital Senior Leadership Team wants to explore the opportunity of creating a Joint Replacement service line in order to better serve the needs of the hospital catchment area. A project team is set up to investigate the strategic opportunity, the sizing and characteristics of such a service line, based on the population needs and the hospital strategy, and then make a recommendation.

The team has chosen to be guided by the COM Functions Table (Table 5-2 Case Study coverage of COM Functions Table in section 5.3.2), focusing on the top 2 rows related to Strategic & Tactical decision levels.

Here is the detailed scenario:

- Service Line Management: the demographics of the hospital catchment area and the healthcare need analysis conducted by the team show that the need for Hip & Knee Replacement is much higher than what the hospital can deliver today. Following the QBP, the patient cohort selection criteria have been identified, thus giving an indication of the annual volume of procedures the service line would have to meet, along with the mix of Hip versus Knee procedures.
- Demand Capacity Management: the Simulation of the service line composed of both services, with annual volumes as input (the Demand), has given a good understanding of how many ORs are required and how best to allocate cases to each OR. Using the Optimization Tool, the team has created a Master Surgery Schedule with slots and OR allocated to Surgeons for every day of the week. This told the team how many Surgeons would have to be recruited, how many OR

Nurses would be required and what their shift schedule should be. This also told the team how many beds in the Surgery Ward(s) are required, and hence how many Ward Nurses would have to be recruited.

- Human Resources Management: following the previous simulation and optimization, the team investigated the workforce planning, recruitment, training, and organization. They also investigated the Nursing and Physician organization which would best meet the needs of the service line.
- Supply Management: based on the annual volumes, the number of ORs, the number of Surgeons, the team investigated the volumes of Joint prosthesis required, based on types and sizes and brand preferences of the Orthopedic Surgeons. They also looked at the equipment that the ORs would require.
- Performance Management: Performance Indicators were analyzed, identified, and selected. Target levels were set which have an impact on Capacity Management, and required iterative analysis.
- QoC, Risk, and Safety Management: Policies were investigated, and targets set which had an impact on Performance Management and Capacity Management, thus requiring more iterations.
- Accounting Management: Collect the direct and indirect cost information about the Joint Replacement service line, and compute the Average Cost per Weighted Case, and on an on-going basis, compute the cost for each weighted case in near real-time, in order to assess whether the hospital can sustain the delivery of Hip & Knee Replacements at a weighted case cost lower than the reimbursement level set by Ontario (which is the average cost of such procedures across the province).

Now, assuming the team's recommendation to create the service line has been accepted by the Senior Leadership Team, the next phase of the project is to build hospital-specific COM Models, UML/BPMN/DMN Models, and COSS Modules.

- An Orthopedic Surgeon has volunteered to be trained on COM modeling, and started to customize the generic COM Models to the specific needs of the service line.

- One Health Informatics Analyst has been trained on the entire COM Platform, and joined him for the UML/BPMN/DMN modeling. The most challenging task had been the manual weaving of the UML, BPMN, and DMN models together.
- One Software Engineer from the IS Department has also been trained on the entire COM Platform, and joined them for the COSS generation and build. She was also able to help the Analyst with the weaving of the UML, BPMN, and DMN models together.

Another task for the project is the new organization of the service line.

- A Service Line Director has been appointed
- A Service Line Nursing Coordinator has been appointed, covering all the Units under the new service line.
- The organization structure has shifted from Vertical to Matrix, where everyone in the Units covered by the service line would now report to 2 bosses: the functional Unit Director, and the Service Line Director.

This Use Case 3 is showing the value of a structured framework like the COM Functions Table in ensuring that hospitals conduct a systematic, thorough, iterative, multi-disciplinary analysis of the service line before making the decision. Today, this is done in an ad hoc way, often driven mostly by the Finance department, with incomplete data and information.

The Use Case 3 exercises the following COSS Modules

- Engineering Tools: Optimization, Simulation
- Demand Mgt DSS
- Capacity Mgt DSS
- Master Schedule
- Case Costing and Accounting Mgt
- Human Resources Mgt
- Supply Mgt
- COOM3

- And provided inputs for the Performance Mgt, Qoc/Risk/Safety Mgt, and Service Line Mgt modules.

This Use Case 3 has enabled us to understand, research, and design the Capacity Mgt DSS and the Demand Mgt DSS, working together with the Engineering Tools and the other COSS Modules, using the COOM3 blackboard. For Use case 3, the DSS were simulated with scripted requests/responses/events.

Use case 4: Service Provisioning

A Knee Replacement Patient is being booked by the Surgeon's office who contacts the hospital OR Booking Office. This is the Operational Off-line decision-making row in the COM Functions Table.

- The OR Booking Office Clerk uses the Demand Mgt DSS, Capacity Mgt DSS, and the Master Surgery Schedule (valid for 4-6 months usually). Once the Clerk has entered all relevant information about the Case, Patient, Surgeon, Procedure, the DSS start working on a recommended schedule slot (day, time, OR) for the procedure.
- The DSS are trying to pick the best slot in terms of Surgeon's preferences (a difficult case would usually be scheduled early in the morning), OR utilization, bed occupancy in the Surgery Ward following the operation, OR overtime avoidance, while keeping the patient wait time as low as possible (30 days, for instance), and while anticipating the possible emergency patient flow (i.e Hip Fracture) which might happen on that day, based on historical data, and disrupt the schedule.
- The OR Booking Office Clerk proposes the best slot to the Surgeon's Office.
- The Surgeon's Office confirms the booking
- Automatically, the DSS start service provisioning for this Patient, and inform the other COSS modules
 - OR and Timeslot scheduling for Anesthetist
 - Nursing staffing

- Procedure Card provisioning for the case
- Surgery ward bed reserved
- Rehab planning
- Transportation to/from hospital
- Post-discharge follow-up planning

The Use Case 4 exercises the following COSS Modules:

- Demand Mgt DSS
- Capacity Mgt DSS
- Master Schedule
- Rules Mgt, Rules Engine, Rules Repository
- COOM2

This Use Case 4 has enabled us to understand, research, and design the Capacity Mgt DSS, using the Master Schedule, and the Demand Mgt DSS, working together using the COOM2 blackboard, as described in section 4.6. For Use case 4, the DSS were simulated with scripted requests/responses/events.

Use Case 5: Service Delivery

The Knee Replacement Patient arrives at the hospital at 07:00 on the booked day, for Same Day Admission and Procedure. This is the Operational On-line decision-making row in the COM Functions Table.

- At 07:30, the Patient is admitted and brought to the OR area for pre-operative preparation. The procedure is due to start at 09:30, for a duration of 1.5 hours. From this moment on, the Patient is followed by the 5 DSS working together using the COOM1 blackboard.
- If the hospital is in Full-Capacity Protocol, the procedure might be delayed later in the day. Before, without COSS, the procedure might have been cancelled, and the patient sent home and re-booked for a later date.

- At 09:20, the Patient is brought into OR7. After having checked that everything is in place, the Surgeon starts the Safe Surgery Check-list. The results of the check will be recorded by the QoC, Risk, & Safety Mgt module. Another check will take place at the end of the procedure, before the Patient leaves OR7, recorded by the module. If anything non-nominal had happened, the Adverse Event Management module would have recorded the event.
- At 09:30, the Surgeon starts the incision.
- The scenario continues along the same lines as Use Case 1...

The Use Case 5 exercises the following COSS Modules:

- Real-Time Patient Flow Mgt DSS
- Operational Business Intelligence DSS
- Rules Mgt, Rules Engine, Rules Repository
- Service Line Mgt, Patient Cohort Mgt, Ancillary Service Mgt
- Real-Time Demand Capacity Mgt
- Demand Mgt DSS, Capacity Mgt DSS
- Full-Capacity Protocol DSS
- Unified Communications
- COOM1

This Use Case 5 has enabled us to understand, research, and design the Real-Time Patient Flow Mgt DSS, the Operational Business Intelligence DSS, the Demand Mgt DSS, the Capacity Mgt DSS, and the Full-Capacity Protocol DSS, working together using the COOM1 blackboard, as described in section 4.6. For Use case 5, the DSS were simulated with scripted requests/responses/events.

5.3.6 Results

The COM Models and UML/BPMN/DMN Models for the Joint Replacement Service Line have been built. They have been discussed with Orthopedic Surgeons and OR

Nurses, and with Analysts at both hospitals, in several iterations, when we were doing the value stream mapping of these clinical services. The Surgeons and Nurses found the COM Models very useful in helping them formalize and document their practice; they also better understood the bigger picture of the complex interaction between their clinical processes and the administrative ones (Finances, Human Resources, Supply Chain).

The three use cases have exercised all the modules of the COSS lab prototype for Joint Replacement service line, and shown its technical feasibility. It has to be noted that the DSS were simulated with scripted requests/responses/events.

5.4 Case Study 3: Tools for Model-Driven COM

The goal is to prove the technical feasibility of tool support for the model-driven COM enterprise architecture.

5.4.1 Lab Prototype of COMP Tools

The goal of the lab prototype is to validate COMP and its MetaModel.

The COMP Modeling Tool is composed of:

- the Eclipse Papyrus for UML Stereotyping.
- the Modelio editor for COM Modeling, for BPMN and (soon) DMN modeling
- the View/Model Repository, which contains the model libraries
- the Engineering tools: Discrete Event Simulation, Optimization, MCDA

We first use Papyrus to create the COMP MetaModel, i.e the UML Profile for the COM Domain, with Stereotypes, Tags, and Constraints. Papyrus is particularly good for stereotyping by offering more flexibility than other tools. The screenshot on Figure 5-24 below shows the Papyrus model view on the left, the Papyrus diagram view in the center, the diagram palette on the right, the diagram outline (i.e zoom out view showing what the diagram view shows of the entire diagram) on the bottom left, and a set of element editors on the bottom right.

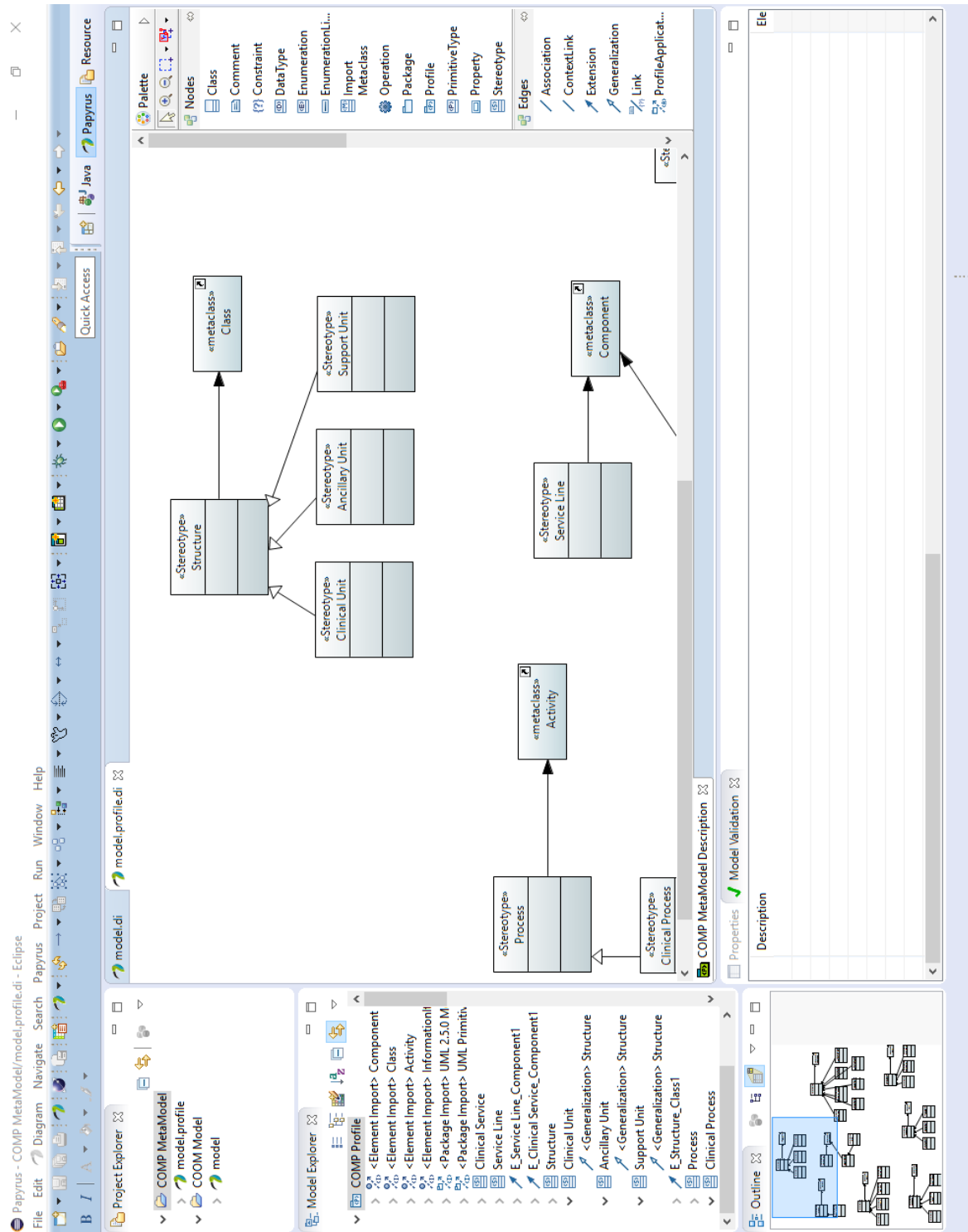


Figure 5-24 Screenshot of Papyrus for COMP Stereotyping

The COMP MetaModel is then applied in Modelio which is easier to use than Papyrus for COM modeling. Both tools have an Audit function to validate the MetaModel. It is automatically validated by Papyrus because it would not allow an invalid model being built, with its automatic audit feature. The Modelio screenshot on Figure 5-25 shows on the bottom that the MetaModel audit has been successful, with 0 error/warning/advice. The screen layout of Modelio is similar to the Papyrus screen layout. Figure 5-26 zooms in on the Modelio model view on the right, the Modelio diagram view at the center, and the audit results at the bottom.

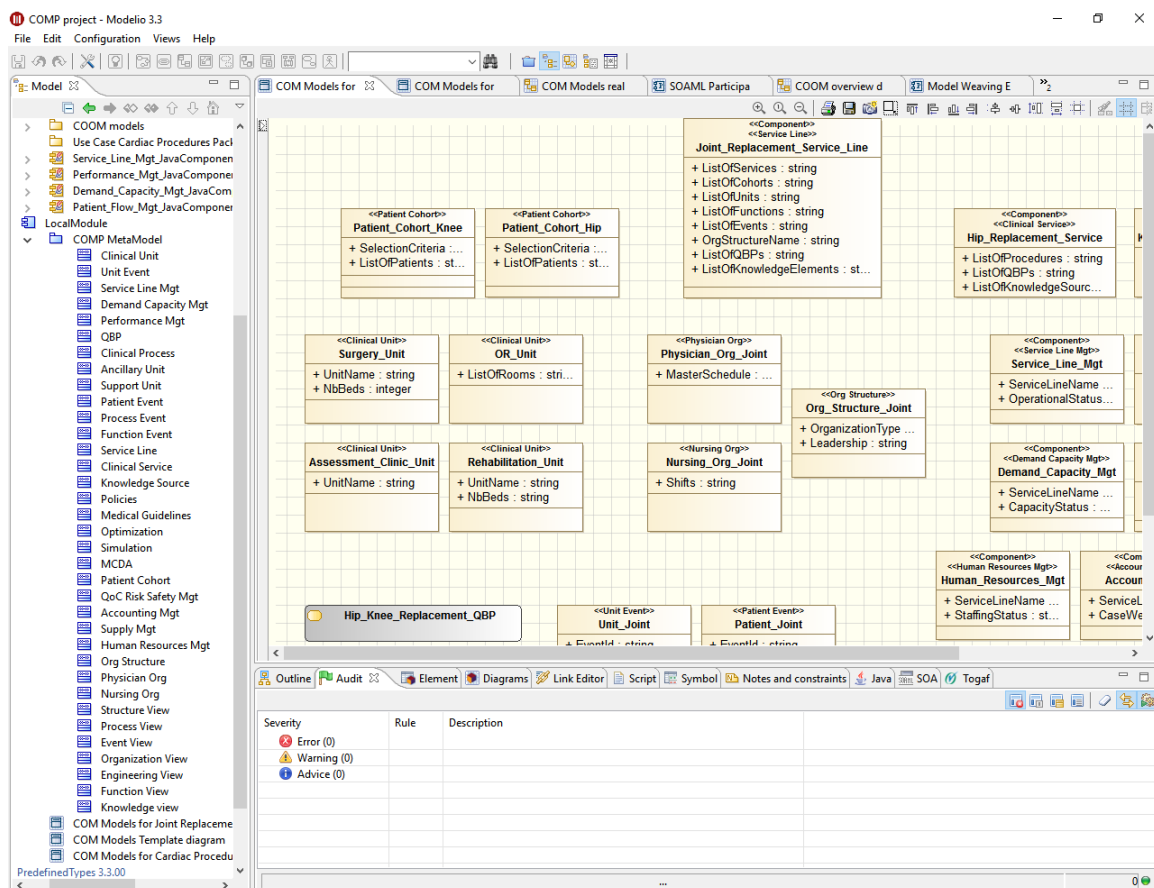


Figure 5-25 Screenshot of Modelio with COMP Stereotypes

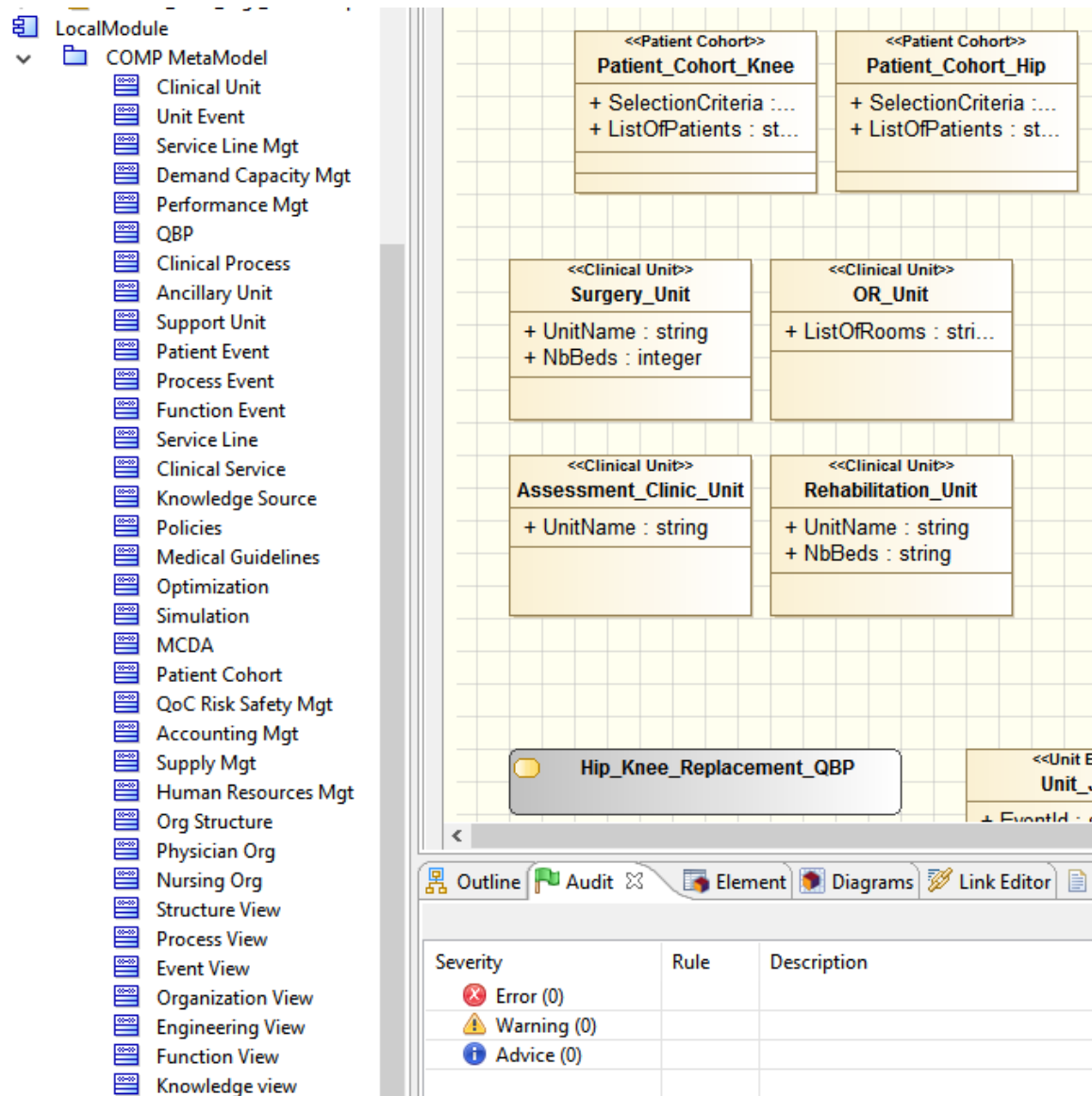


Figure 5-26 Screenshot of Modelio showing COMP Stereotypes Audit

Then, the Clinicians start building the COM Models for service lines in a specific hospital, with Modelio. Figure 5-27 and 5-28 respectively show the COM models for the Cardiac Procedures Service Line and the Joint Replacement Service Line. This is the step when the model customization for the hospital takes place. Clinicians update the model view on the right with custom attributes and operations, and see the diagrams updated automatically.

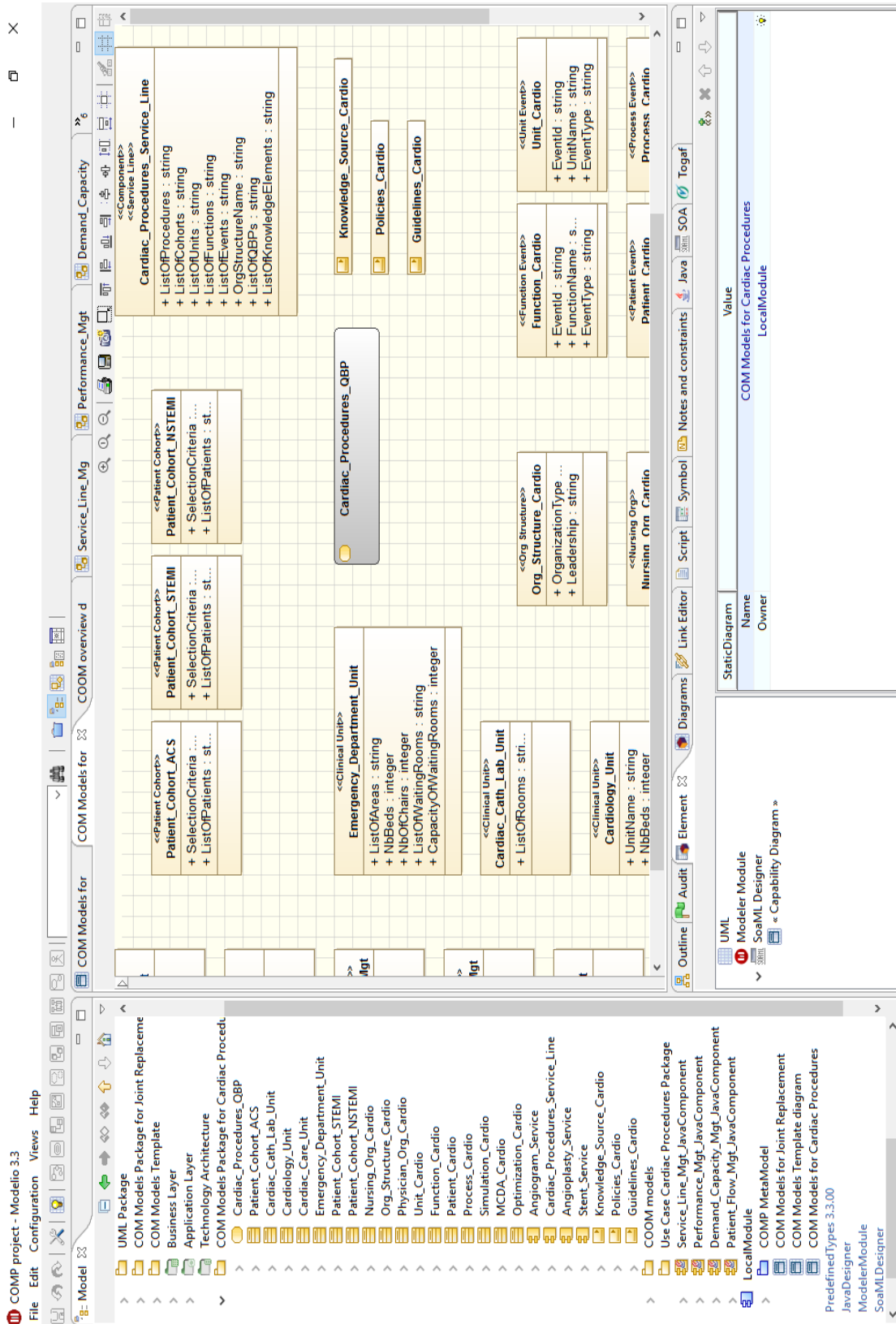


Figure 5-27 Screenshot of COM Modeling for Cardiac Procedures Service Line

From then on, the Health Informatics Analysts take over the UML/BPMN/DMN modeling with Modelio. The screenshot in Figure 5-29 shows the SOAML modeling of SOA services between Participants, with their Components listed within them.

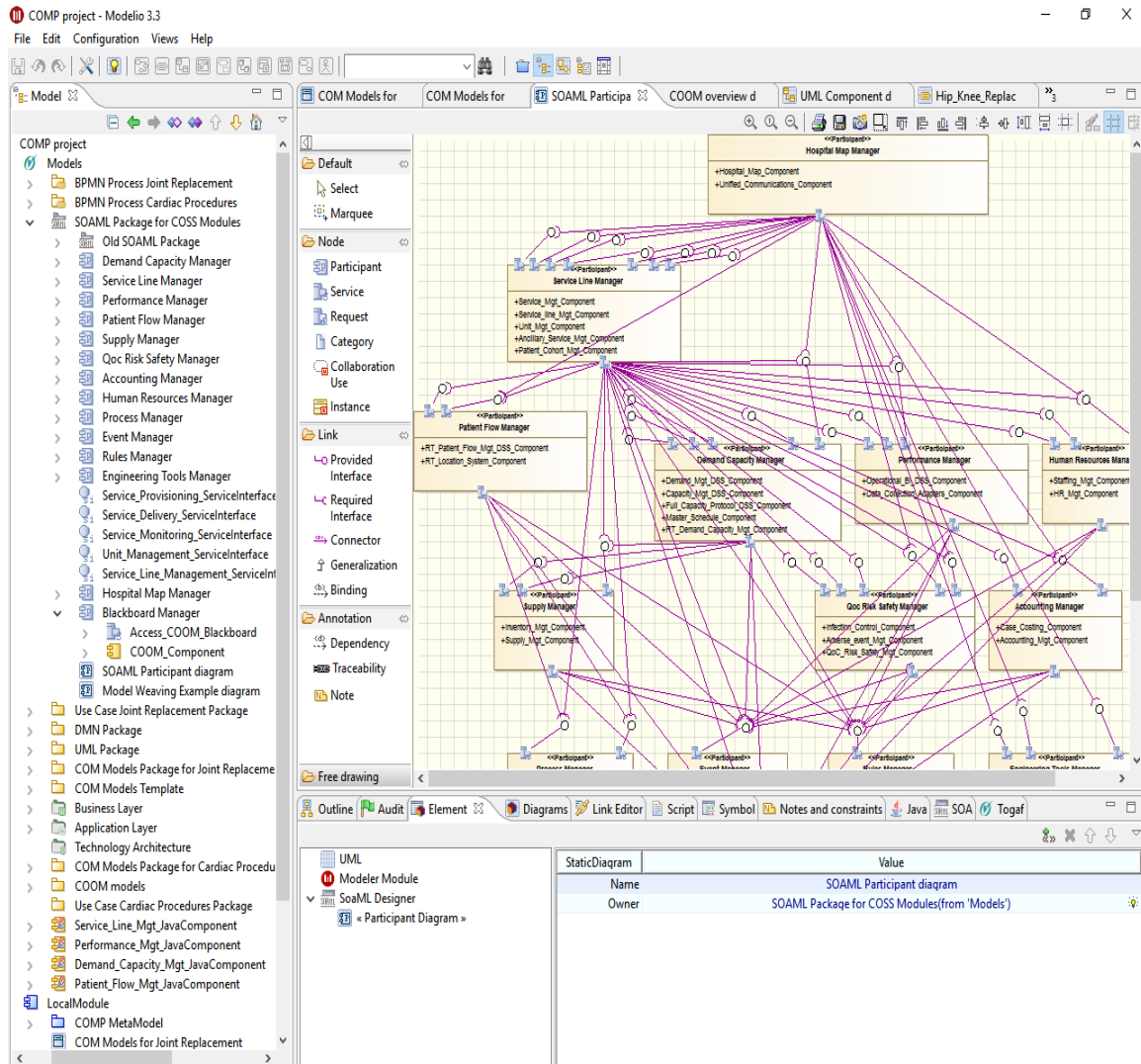


Figure 5-29 Screenshot of Participants, Components, and Services

Modelio is then used for the COOM modeling of the Blackboard structure. The screenshot in Figure 5-30 shows the modeling of COOM1 for the Joint Replacement Service Line.

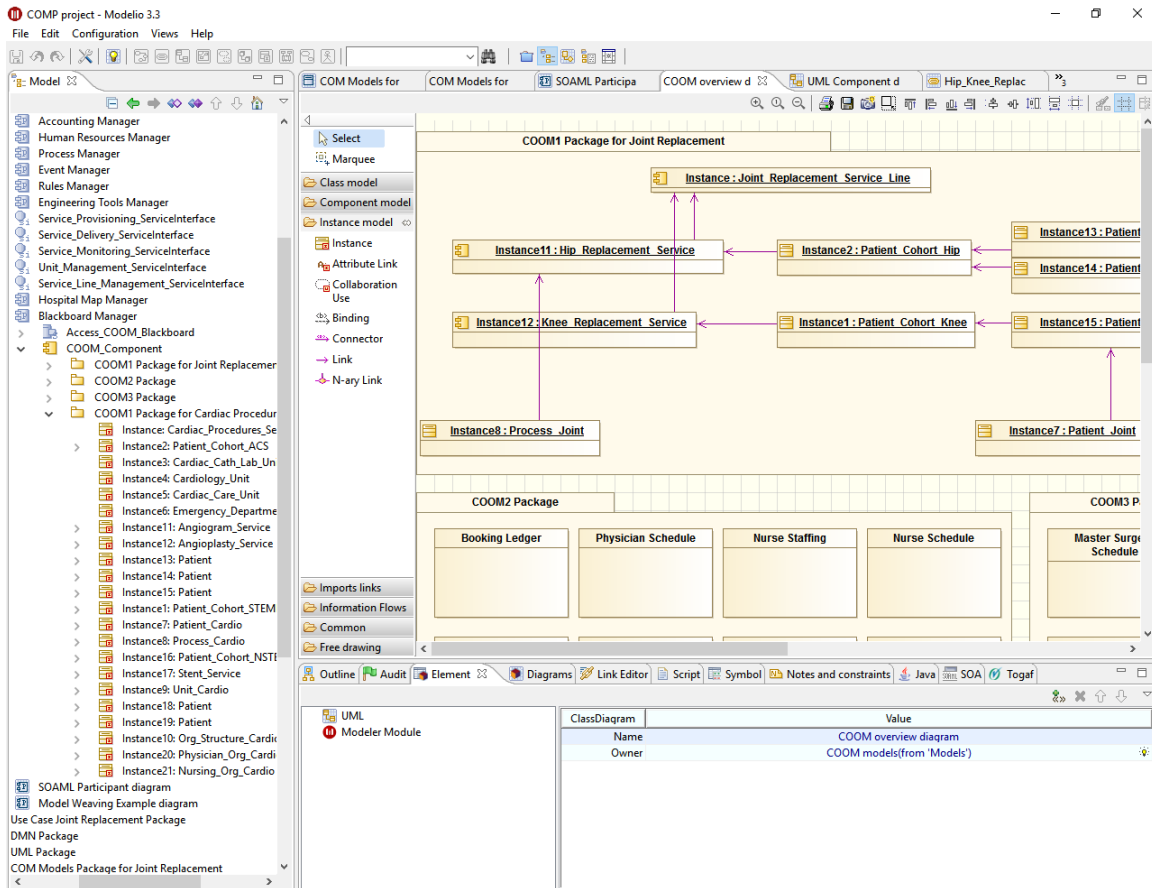


Figure 5-30 Screenshot of COOM Modeling

Assembling the lab prototype of the COMP Modeling Tool is straightforward because Papyrus and Modelio have been designed to work together in the Eclipse environment, and support the same model interchange format.

This Lab Prototype of the COMP Modeling Tool has been used for building the COM and UML/BPMN/DMN models of the first two case studies in sections 5.2 and 5.3. It validated the COMP MetaModel as a UML Profile.

5.4.2 Lab Prototype of COSBench

The goal of this lab prototype of COSBench is to generate COSS Modules from the UML/BPMN/DMN models in order to show the feasibility of an integrated tool suite: COMP Tools + COSBench.

COSBench is composed of:

- Modelio or Acceleo for UML Model-to-Java code generation
- Acceleo for UML Model-to-Text generation. The text is scripts for the Engineering Tools.
- Modelio or DROOLS or Camunda for the BPMN Model transformation and execution by their Process Engine
- DROOLS Fusion for the Event Rules and Event Engine (Complex Event Processing). Does not support DMN modeling yet; therefore, the Event Rules would have to be in their Drools Rules Language
- Camunda for the DMN Model transformation and execution by their Rules Engine
- All these tools support the XMI model interchange standard; they are therefore inter-operable
- A set of COSBench Libraries. They are implementing the functional core of the DSS described in sections 4.6.5 to 4.6.8. These COSBench Libraries have been designed, but not completely implemented yet. This will be part of future work.
- Tools for Fast-Forward Simulation (FFS) and Multi-Criteria Decision Analysis (MCDA). They are used by the COSS DSS, specifically the Full-Capacity Protocol DSS. The usage of these tools differs from the one of the Engineering Tools of the COMP Tools: they are used at run-time instead of modeling time.

With Modelio, we generated the COSS Lab Prototypes of section 5.2.5 and 5.3.5, based on the COM Models in sections 5.2.3 and 5.3.3. The code generation was partial: just enough code has been generated to verify the feasibility of an integration of COSBench

with the COMP Tools. This includes the generation of COOM interfaces. These COSS Lab Prototypes were originally built manually.

We also generated a stub for the HL7 Adapters to EMR module, and checked that an HL7 ADT message (for Admit/Discharge/Transfer information about a patient) could be received from the Meditech EMR used at the hospital. The COSS is designed to be an overlay system communicating with the EMR; therefore, HL7 messaging is important. We also checked that the COM UML information models did not have any side effect with the HL7 Reference Model that we could see, and that we could handle the ICD9 codes (International Statistical Classification of Diseases and Related Health Problems) in the messages.

Figure 5-31 below shows a screenshot of Modelio for the Java code generation from UML models.

Figure 5-32 shows the Modelio Model-Driven Code Generation strategy for preserving any custom code written between Markers, thus creating a preserved area not impacted when code has to be re-generated, and also for preserving the UML model integrity.

Figure 5-33 shows another way from Modelio to insert custom code at the right place in the generated code and preserve the UML model integrity: Notes written in the Java syntax are added to model elements at the right place by using Notes types.

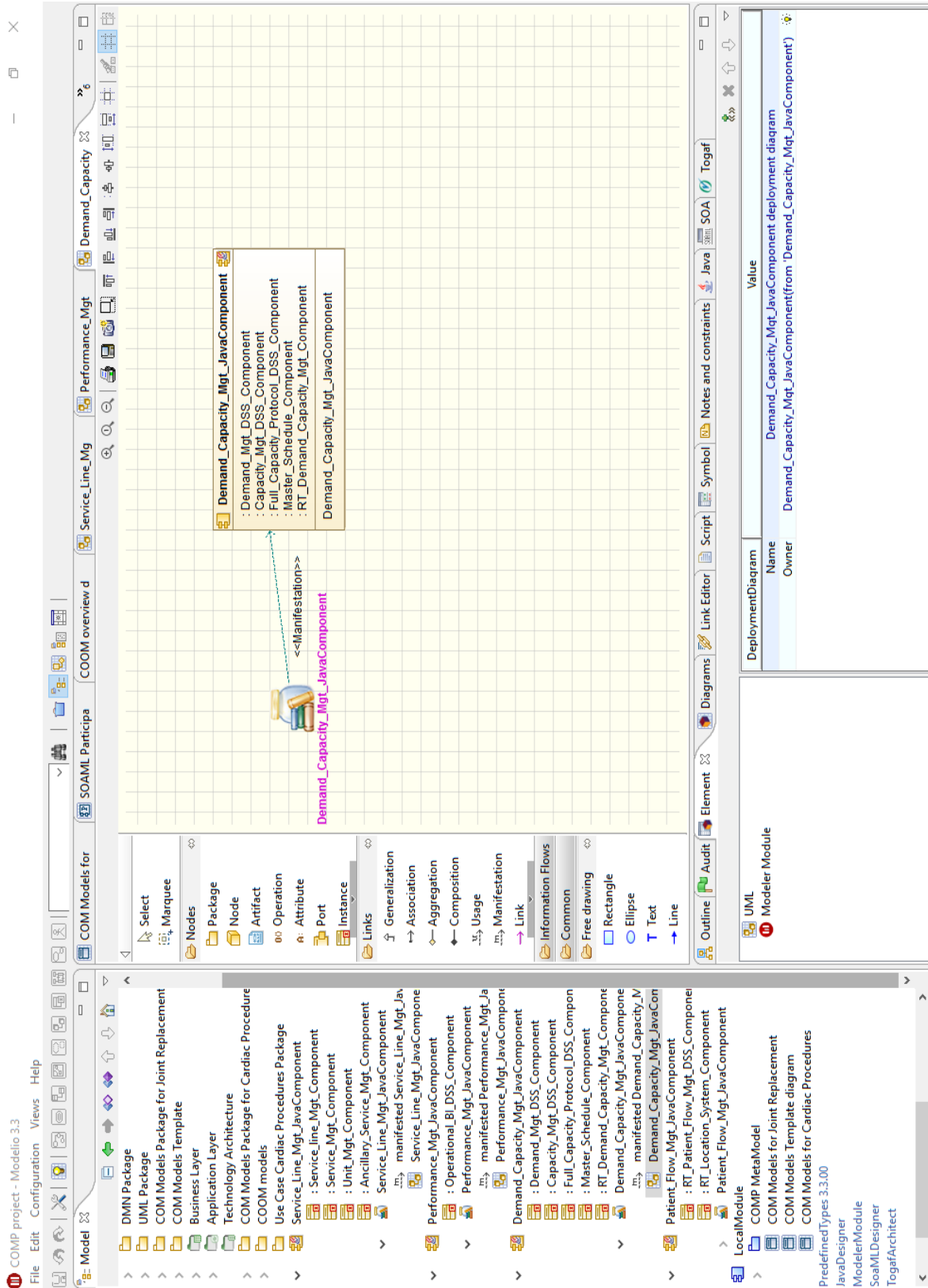


Figure 5-31 Screenshot of COSBench Java code generation

With this approach, the model is developed and then the code generated, with authorization to write method code only between markers in the Java code. Modelio is therefore in charge, with Eclipse being used to complete the skeleton of produced code. In theory, this is the recommended mode, since it guarantees that model-level design is respected. Below, we see the comments marking up the beginning and the end of code that can be changed by the programmer (procedural code).

```
public Product order(final String orderedProduct) {
//begin of modifiable zone(JavaCode).....C/3a0ca6e8-f99c-11e0-ad97-58946b108de1

. . .you can enter your application code between the markers

//end of modifiable zone(JavaCode).....E/3a0ca6e8-f99c-11e0-ad97-58946b108de1
//begin of modifiable zone(JavaReturned)..C/3a0ca6e8-f99c-11e0-ad97-58946b108de1

//end of modifiable zone(JavaReturned)...E/3a0ca6e8-f99c-11e0-ad97-58946b108de1
}
```

Note that in model-driven mode, the developer is not expected to introduce any additional code outside the markers, i.e. he or she cannot add any attribute or method definitions, imports or classes, nor can he or she modify any existing method signatures. This makes the model-driven approach a highly secure, if somewhat constrained, mode.

Figure 5-32 Modelio Model-Driven Code Generation

Overview

Modelio Java Designer notes are used to complete the UML model with texts expressed in Java syntax. Usually, the internal processing of a UML method is entered in Java in a JavaCode type note associated to a methods implementation.

Note: Certain notes can be added to certain model elements directly through the Java tab. For more information, please see [Java Designer property view](#).

Type of notes on a class

The ... type of note	Label	Is used to...
JavaHeader	Header	insert a text before declaring the class.
JavaMembers	Members	insert a text in the class body.
JavaBottom	Bottom	insert a text after declaring the class.
Javadoc	Javadoc	add a comment to be used by javadoc.
JavaTop	Top	insert a comment before the java file's package instruction.
JavaAnnotation	Annotations	specify the annotations added to the class.

Type of notes on an operation

The ... type of note	Label	Is used to...
Javadoc	Javadoc	add a comment which will be used by javadoc.
JavaCode	Code	provide Java code for implementing the operation.
JavaSuper	Super	insert Java code before the pre-condition (especially for calling the builder of the parent class).
JavaReturned	Return code	insert Java code after the post-condition (especially for instructing the method return).
JavaAnnotation	Annotations	specify the annotations added to the operation.

Figure 5-33 Modelio Java Notes Types for Code Generation

The COSBench Lab Prototype has enabled us to better understand the following, and the results are previously described in section 4.6:

- COSS module design (section 4.6.2)
- Customizability provided by the Rules engine (with DMN models), Process engine (with BPMN models), CEP engine (with DMN models) which are separated from the code itself and the models. This Separation of Concerns supports the customization to specific hospital needs by simply updating the models, without having to regenerate code (section 4.6.9)
- Generation of the COOM blackboard data structure and Knowledge Source interfaces to the blackboard data structure (section 4.6.3)
- Guidelines for the design of Knowledge Sources (section 4.6.4)

5.4.3 Results

The technical feasibility of the COM Platform is confirmed. Therefore, we benefit from the documented added value of Model-Driven Engineering of COSS compared to the manual development of COSS: shorter development time, less bugs, better traceability of requirements.

The manual development of the 39 COSS Modules for the Joint Replacement Service line of section 5.3.5 has taken 6 weeks. The COSS Lab Prototype was incomplete, and had only enough code to validate the Use Cases. Using Figure 4-54 in section 4.6.2, only the SOA interfaces, the COOM interfaces, and some functional code inside the modules were developed for the Use Cases. In particular, the COSBench Libraries developed during the design of the 5 DSS (Demand Mgt, Capacity Mgt, Full-Capacity Protocol, Real-Time Patient Flow Mgt, and Operational Business Intelligence) were not integrated but simulated with scripted request/responses/events.

The automatic development of the same 39 COSS Modules, to the same level of incompleteness, using the integrated COMP Tools + COSBench has taken 1 week. The main challenge in an industrial-grade COSS generated with COSBench is the “glue” linking the generated SOA interfaces and COOM interfaces to the COSBench Libraries. We used the Modelio Markers and Notes types for the “glue”. Once the Libraries finalized, which they are not currently, this “glue” could become another COSBench Library that the hospital IT team could extend if required, thus reducing even more the use of tool-specific solutions like Modelio’s Markers and Notes types.

5.5 Case Study 4: Architecture Analysis of COM Platform

The goal is to prove the generalization of the COM Platform architecture to all hospital types and all service lines.

5.5.1 Architecture mechanisms

The following main architecture mechanisms have been validated for the 2 case studies of Cardiac Procedures and Joint Replacement service lines (sections 5.2 and 5.3):

- MDE, based on standards and existing tools: from CIM (COM Models) to PIM (UML/BPMN/DMN models), and then to PSM (COSS Modules)
- Enterprise Architecture based on TOGAF: COM Models describing the Business Architecture, UML/BPMN/DMN models describing the IS Architecture, and COSS Modules describing the Technology Architecture
- Separation of Concerns between medical/clinical concepts from IS concepts: Clinician-friendly COM models
- Separation of Concerns between models containing domain-specific knowledge (UML information models, BPMN process models, DMN Rules and Event Rules) and software components processing this knowledge
- Customizability of models and COSS for each hospital, by editing the models and then re-generating the code for COSS Modules

- COSS is supporting new services/service lines mostly based on editing new models: generalizability
- Model-Based Reasoning, based on the Blackboard Architecture Pattern: COOM, Knowledge Sources, and DSS
- Coupling of different software design paradigms: MDE, Business Process Management, Event-Driven Architecture, Rules-Based system, Model-Based Reasoning. This mix of loose coupling based on the SOA interface and strong coupling based on the COOM blackboard has enabled the COSS to support functional integration of care, process integration of care, and transitions of care.

The following analysis is to ensure that the architecture mechanisms still work as planned for other service lines and other hospital types. This generalization analysis technique is called Architectural Inference [Wieringa2013].

5.5.2 Architectural Inference on service lines

Because of the separation between medical/clinical concepts and the information system concepts, most of new services and service lines could be supported via new models (section 4.7.9). It is only when new functions are required to support these new services or service lines that some code has to be written, and the COSS re-built. We have undertaken a non-exhaustive analysis of the following QBP and how the COM Platform could support them:

- Chronic Kidney Disease
- Chronic Obstructive Pulmonary Disease
- Pneumonia
- Stroke
- Congestive Heart Failure
- Coronary Artery Disease
- Aortic Valve Disease
- Hip Fracture
- Cataract Surgery

- Cancer Surgery

These QBP represent a good spectrum of services or service lines, and cover all the following dimensions of hospital care:

- Chronic vs Acute
- Inpatient vs Outpatient
- Medicine vs Surgery
- Emergency vs Elective
- Need for Pre/Post Clinic

These are explicitly supported by the COM Platform, with the definition of clinical services, units, and processes.

Analysis of Chronic Obstructive Pulmonary Disease (COPD) QBP:

COPD is a chronic respiratory disease with acute exacerbation episodes which may require admission to a hospital. It is chosen here because it is quite different from the Cardiac Procedures and Joint Replacement case studies. Here is the care pathway per the Ontario MOHLTC QBP [QBP].

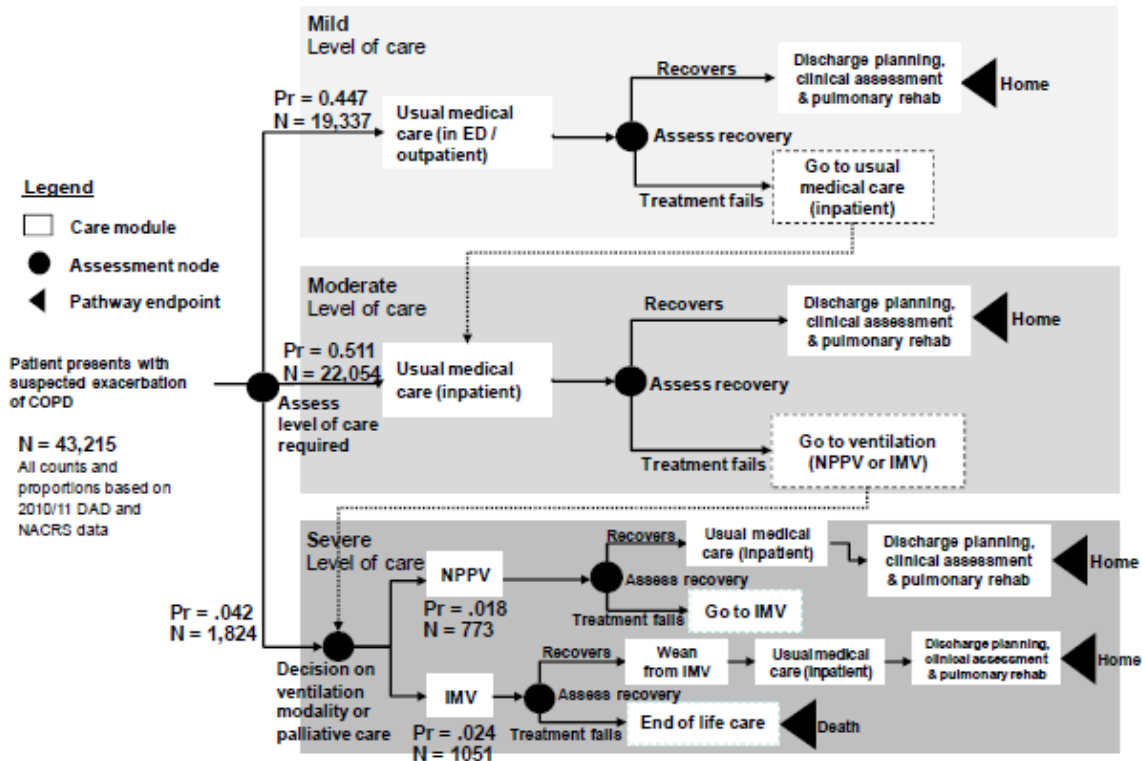


Figure 6: COPD Acute Exacerbation Episode of Care Model

Figure 5-34 COPD QBP [QBP]

Analysis:

- Service Line: Respiratory Diseases
- Clinical Service: COPD
- Patient Cohorts: Mild COPD, Moderate COPD, Severe COPD
- COM Models
 - Units: Emergency Department, Outpatient Care, Medicine Unit, Intensive Care Unit, Pulmonary Rehabilitation Unit
 - Process: COPD QBP
 - Functions: all
 - Events: service-specific events of all types
 - Organization: matrix, like in the case studies, with new positions of Service Line Director and Service Line Nursing Coordinator
 - Knowledge: service-specific Knowledge Sources, Policies, Guidelines

- Engineering: Simulation, Optimization, MCDA of service line
- Same list of SOAML Participants and Components as in the case studies, but processing different COOM1 information model, BPMN processes, and DMN Rules/Event Rules. Same weaving technique linking the models together.
- Same COSS Module Architecture, with 1-to-1 mapping to the Components, but with slightly different code following the COSBench code generation.

Analysis of the other 9 QBPs:

The analysis, similar to the one above for COPD, is showing that these 9 QBPs can be supported by updating the COM Models. No new Function is required. Same list of Components, but processing different COOM1 information model, BPMN processes, and DMN Rules/Event Rules. No new custom code is needed. The COSS Modules would have to be re-generated.

The architecture mechanisms described in section 5.5.1 work exactly the same way.

Applying Architectural Inference, we can infer that the COM Platform supports these QBPs as well. However, a more thorough validation would have to be done as part of future work.

5.5.3 Architectural Inference on hospital types

The main hospital types are:

- Community hospital: this is the reference we have used for our case studies; they usually constitute the bulk of hospitals.
- Rural hospital: they are smaller hospitals, do not have as many types of units as a community hospital, and do not deliver as large a set of clinical services.
- Teaching hospital: they are usually bigger hospitals, deliver a more exhaustive and complex set of clinical services, have an additional mission of teaching interns/residents and conducting clinical research, and usually face more complex scheduling & staffing because of the medical students.

- Tertiary hospital: they are specialized hospitals like Cardiac institutes, Children hospitals, Mental Health hospitals, Complex Continuous Care hospitals, Palliative Care hospitals.

Table 5-3 below summarizes the analysis for these 4 types of hospitals:

Table 5-3 COM Platform architecture analysis based on hospital types

COM Platform for hospital types		Community Hospitals	Rural Hospitals	Teaching Hospitals	Tertiary Hospitals
COM Models	Service Lines; Clinical Services; Patient Cohorts	Reference	limited number of service lines and clinical services	larger number of service lines and clinical services; more complex services; more complex patient flows	limited number of service lines and clinical services; much more complex services
	Structure View	Reference	limited number of units; more hybrid units (medicine & surgery); more general medicine units	larger number of units and types of units	larger number of units of same type
	Process View	50 to 80 care pathways and QBPs	fewer care pathways and QBPs	more care pathways and QBPs (up to 300 pathways)	fewer care pathways and QBPs, but more complex
	Function View	7 Functions	Service Line Mgt is much less developed; other functions are less complex	All 7 Functions, more complex: particularly Demand Capacity Mgt, Performance Mgt, Human Resources Mgt	All 7 Functions, with comparable complexity
	Organization View	Matrix	More vertical than matrix	Matrix	Horizontal
	Event View	Reference	Less complex	More complex	Comparable
	Knowledge View	Reference	Less extensive	More comprehensive	More specialized
	Engineering View	Reference	Lower need for optimization, simulation, MCDA support	Higher need for optimization, simulation, MCDA support	Higher need for optimization, simulation, MCDA support
UML/BPMN/DMN Models	List of SOAML Participants	Reference	same	same	same
	List of UML Components	Reference	fewer Components, depending on Functions needed by hospital	same, plus Components for Teaching Mgt and Research Mgt	same
	COOM1 Information Model	Reference	less complex	more complex	more specialized
	BPMN Process Model	Reference	fewer processes	more processes and more complex	fewer processes but more complex
	DMN Rules/Event Rules	Reference	fewer rules/event rules	more rules/event rules, and more complex	fewer rules/event rules, but more complex
	Weaving of models	Reference	simpler	more complex, but same technique	more complex, but same technique
COSS Modules	List of COSS Modules	Reference	fewer Modules, depending on Functions needed by hospital	same, plus Components for Teaching Mgt and Research Mgt	same

The architecture mechanisms described in section 5.5.1 work exactly the same way. COSS code would have to be re-generated for each hospital type.

Applying Architectural Inference, we can infer that the COM Platform supports these hospital types as well. However, a more thorough validation would have to be done as part of future work.

5.6 Case Study 5: Business Analysis of Hospital Transformation

In this case study, we take a reference hospital transformation and do a comparative analysis of the strengths and weaknesses of our proposed Model-Driven transformation approach with our COM Platform against current practice. The data used is a combination of data from the 3 hospitals; it is therefore realistic but does not reflect the actual nor current indicators at any specific hospital. Furthermore, this case study does not reflect any possible growth strategy of the hospitals.

5.6.1 Reference Hospital Transformation

The reference hospital transformation is defined in terms of a large community hospital, with 250 beds. An EHR is in place. Some clinical information systems have been deployed: ED information system (data-driven; not driven by care flows); OR Management system (data-driven; not driven by care flows); Bed Management system (data-driven; disconnected from EHR). However, there is no information system for Medicine/Surgery Wards; no Business Intelligence system; and no Adverse Event Management system. The clinical information systems do not interoperate with the Finance, HR, and Supply Management systems.

Driven by the Funding Reform of Ontario hospitals, the hospital has to gradually become value-based by delivering an increasing list of Quality-Based Procedures. It has decided to do so in creating 5 new Service Lines:

- Respiratory Diseases
 - Chronic Obstructive Pulmonary Disease QBP
 - Pneumonia QBP
- Cardio-Vascular Disease
 - Congestive Heart Failure QBP
 - Coronary Artery Disease QBP
 - Aortic Valve Disease QBP
 - Vascular (Non-Cardiac) QBP
 - Stroke QBP
- Orthopedic Surgery
 - Hip & Knee Replacement QBP
 - Hip Fracture QBP
- Eye Care
 - Cataract Surgery QBP
 - Integrated Retinal Care QBP
- Cancer Care
 - Cancer Surgery QBP
 - Chemotherapy (Systemic Treatment) QBP

How the hospital decided on the 5 new Service Lines is described in section 5.3.5 Use Case 3: they analyzed the health care needs of their catchment area population; then they analyzed whether they could deliver the clinical services with the highest possible QoC at an Average Cost per Weighted Case lower than what is reimbursed by Ontario; finally, they make a business decision after consultation with the Ontario MOHLTC.

Once the COSS is built for these Service Lines, an interesting question is how do we select the next QBPs in order to minimize the impact on the COSS? We look for similarities in the Care Pathway sequences:

- For instance, a COSS able to handle Hip & Knee Replacement could be fairly easily extended to support other Elective Surgery procedures.

- For instance, a COSS able to handle Hip Fracture could be fairly easily extended to support Emergency Surgery procedures.

5.6.2 Hospital Transformation based on COM Platform

The hospital took the transformation as a strategic opportunity to redesign itself (which is what the MOHLTC is really hoping for). The transformation is structured, systematic, and holistic, based on Model-Driven Transformation, with the use of the COM Platform. A Transformation Office (Project Management, LEAN, Change Management) has been created, leading the hospital through process redesign, organization redesign, and IS redesign, done in parallel.

- Process redesign:
 - The Clinicians have analyzed the clinical impact of QBPs, and the paper-based care processes have been re-aligned within each unit and across all units, ensuring end-to-end continuity of care.
 - The Clinicians, with help from Analysts, designed the new COM Models.
 - The work took place over a 1-year elapsed time.
- Organization redesign:
 - With the introduction of Service Lines, the hospital moves from a functional organization to a matrix organization, with tighter coordination between units.
 - New positions of Service Line Directors and Service Line Coordinators have been created.
 - Staff has been trained on the dual reporting structure.
 - The new organization has been piloted across the hospital.
- IS redesign (not done yet):
 - The COM Models and UML/BPMN/DMN Models have enabled a better understanding of how to rationalize the existing information systems
 - The Bed Management system will be replaced with the COSS
 - The ED information system and the OR information system have been upgraded to support the new data. The COSS will interoperate with them.

- The COSS will interoperate with the Finance, HR, and Supply Management systems.
- The COSS will provide all the functions defined in the Function view.
- The COSS will be brought in as an overlay on top of existing information systems, and interfacing with them.

The challenges faced in Process and Organizational Redesign are:

- Change Management
- Degree of readiness of hospital management
- Training given to Physicians and Nurses; organizational awareness
- Limited upfront budget for redesign
- Silo approach for OR redesign, instead of systemic approach

The transformation outcomes are the following:

- The matrix organization is optimal for QBP-aligned clinical care. This has led to increased productivity, faster and better decision-making. This new organization will be supported by the COSS.
- The care processes are aligned with the QBPs, end-to-end. They will be supported by the COSS
- The COSS will provide operational performance improvement.
 - Driven by QBPs and Models
 - Aligned with Clinicians' workflows
 - End-to-end, real-time, patient-centered clinical service management
 - No more double/triple data entry
 - Optimization and Simulation of performance before pilot and deployment
 - Performance indicators in ED, Medicine, Peri-Op will improve (see table below).
- The Activity-Based Costing enables real-time financial control: Clinical Directors deciding, for instance, on staffing Nursing to patient census would get the financial impact of their decision within minutes of making the decision, would get a

simulation of the cost over the next day, and would be able to monitor the actual cost versus the predicted cost.

- New functionalities when COSS is available:
 - The Supply inventory control is finally done in real-time
 - Real-time Patient flow management
 - Staffing-to-Census, with real-time Demand Capacity Management
 - Operational Business Intelligence
 - Adverse Event Management; Management of Quality of Care
- High level of COSS customization to specific hospital policies, case mix, patient mix, driven by Clinicians themselves will reduce the cognitive load on the Clinicians during their day-to-day activities, and thus increase their productivity and engagement
- Finally, the most important outcome is for the patients: they are on individual care plans, their recovery is monitored end-to-end during their journey through the entire hospital, their convalescence outside of the hospital is optimized, their patient experience (wait times, quality of service) is significantly improved, and their readmission rate should be decreased. The overall patient satisfaction should significantly improve.

5.6.3 Rol Analysis of Hospital Transformation

This is a calculation of Return on Investment of a hospital transformation done “with COM Platform”.

Because the COSS has not been productized yet, it has been simulated: data was collected manually, processed manually, and reported manually as if by the COSS.

Assumptions:

Here are the assumptions we are making for this quick analysis of Return on Investment (RoI):

- COMP Tools, COSBench, COM Models, UML/BPMN/DMN Models, and COSS Modules are available as Open-Source software, based on our work. The software itself does not cost anything to the hospital. Maintenance, Upgrades, and Support

are provided by COM Support Providers, which are for-profit businesses. This is the business model adopted by OSCAR EMR (see section 2.7). The open source nature of the COM Platform is critical to its adoption by Ontario hospitals.

- A team of 6 Clinicians and Analysts (2 Physicians, 2 Health Informatics Nurses, 2 Health Informatics Analysts) have been trained on the COM Platform.
- A Transformation Office is operational (2 internal consultants), and trained on the COM Platform.
- The hospital Senior Leadership Team provides increased executive support and leadership.
- Same patient volume, with at least the same Quality of Care.

Expenses:

The Model-Based Transformation using the COM Platform incurs upfront one-time expenses that the ad hoc transformation would not have. The upfront one-time investment during Year 1 is the following:

- Cost of setting up the Transformation Office, training, execution of transformation: 300K\$
- Cost of training the Clinicians and Analysts on the COM Platform: 150K\$
- Cost of installing, configuring, and deploying the COM Platform: 50K\$
- Cost of customizing the COM Models, UML/BPMN/DMN Models, and COSS: 100K\$

The annual on-going expenses from Year 2 on are the following:

- Salary expenses of the Clinicians, Analysts, specifically related to the Model-Driven COM initiative: 120K\$
- Cost of COM Platform software maintenance and support: 30K\$

Savings:

Compared to the state pre-Transformation, the on-going annual savings for the hospital are the following:

- Staffing-to-Census: 300K\$
- Less Overtime: 200K\$
- Less Absenteeism: 100K\$
- Increased efficiency/less paperwork/less manual work: 100K\$

The major savings are made with the decreased workload on Nursing. The numbers for Staffing-to-Census, Overtime, and Absenteeism savings are based on hourly compensation & benefits costs of 55\$/hour for Registered Nurses (RN) and 45\$/hour for Registered Practical Nurses (RPN):

- Staffing-to-Census: the bed occupancy in the wards can vary significantly. Most units have between 32 and 36 beds. Normal Patient-to-Nurse ratio in the wards is 4:1 during the day and 6:1 at night; depending on the medical specialties. This means each ward would be staffed with 8/9 Nurses during the day and 5/6 at night, with a RN/RPN mix which depends on hospital policies. Bed occupancy in the wards can vary from 50% to 100% depending on the days. Wards are usually staffed for the maximum occupancy because, without the COSS, it's very difficult to predict bed occupancy 48 to 24 hours ahead of time. However, sending a Nurse home because of low bed occupancy requires 24 hours of advance notice for RPNs and 48hours for RNs, because of Nursing Union regulations. With the COSS Demand Mgt DSS and Capacity Mgt DSS, we should be able to accurately predict bed occupancy ahead of time, that is patient census, and staff accordingly; this is Staffing-to-Census. This would generate significant savings at the ward level; estimates put them at 1 to 2 Nurses per ward (from a pool of 20 to 25 Nurses per ward).
- Overtime: when there is a temporary need for more Nurses, the easiest solution is to ask Nurses to work overtime. Depending on the time of day and the medical specialties, overtime is paid between 25% and 50% more. Units like the OR could incur thousands of overtime hours a year. More accurate prediction of workload, and real-time staffing management across the entire hospital (that is temporarily transferring Nurses from one Unit to another) would significantly decrease overtime.

Return on Investment:

The Return on Investment is of the order of 9 to 12 months. This means that the hospital will be able to recoup the cost of the upfront one-time investment with the savings generated during the same fiscal year. As a consequence, the transformation will have a neutral or positive impact on the hospital budget during the fiscal year when it is taking place. Thereafter, the hospital will generate savings every year.

This Return of Investment analysis is hypothetical but realistic, and is based on the Action Research work done at the 3 hospitals.

Impact on Performance Indicators:

Table 5-4 is showing predicted improvements based on actual numbers we have seen in the 3 hospitals. The COSS is not deployed yet, so the data is based on Process and Organizational Redesign using the COM models, and manual, paper-based improvements to the processes. The data is a compound of data from the 3 hospitals, and is presented to simply give a qualitative sense of the magnitude of the improvements.

Table 5-4 Hospital Transformation with COM Platform

Hospital Transformation with the COM Platform	Before	After
Emergency Department		
90th LoS Admits	20h	13h
90th LoS Non-Admits, High-Acuity	8h	6.5h
90th LoS Non-Admits, Low-Acuity	6h	4h
90th Time-to-PIA	5h	3h
90th Time-to-Inpatient Bed	10h	2h
Medicine Wards		
Bed Occupancy	105%	95%
Average LoS	6d	5d
% patients discharged by 14:00	60%	90%
Surgery Wards		
Bed Occupancy	100%	90%
Average LoS	4d	3.5d
% patients discharged by 14:00	70%	90%
OR		
% procedures start on-time	60%	90%
% procedures completing after hours	10%	5%
% allocated OR utilization	70%	90%
% elective same-day cancellations	10%	3%

Other examples of Hospital Transformation:

The COM models have actually been used to redesign the Future State, compared to Current State, to simulate, optimize, and document, at the 3 hospitals. Here are some application examples, beyond the case studies presented in sections 5.2 and 5.3:

- Redesign of patient flows through an Emergency Department in order to create a zone for cardiac patients
- Redesign the organization and structure of an Emergency Department in order to create 2 zones dedicated to low-acuity patients where 2 dedicated teams composed of 1 Emergency Physician and 1 Registered Nurse provide care during an entire shift. The traditional model is for the Emergency Physician to move from one assessment room to another, and to work with several Nurses concurrently.

- Redesign of the model of care in a Medicine Department, where Physicians are dedicated to a specific unit, where Physician-led multi-disciplinary rounds take place in the morning, where the Nurse staffing is adjusted in real-time based on the patient census, where all discharges are predicted 24h ahead.
- Redesign of the Surgical Master Schedule in order to optimize the OR utilization, and the bed occupancy in the Surgery units, based on the Surgeon's constraints. Traditional schedules only optimize the OR utilization based on the Surgeon's constraints.

6 Evaluation

In section 3.3, we identified two sets of evaluation criteria.

First, a validation analysis is done in section 6.1 to assess how well our COM Enterprise Architecture meets the criteria in section 3.3.1 for value-based hospitals.

Second, a validation analysis is done in section 6.2 to assess how well our MDE approach and COM Platform meet the criteria in section 3.3.2 for the enablement/support of the hospital transformation.

Following this, an analysis is done in section 6.3 comparing our COM Platform against the related work as described in section 2.6. For this comparison, we are using the above criteria.

Then, an analysis is done in section 6.4 on the validation of research hypotheses as described in section 1.3, using the case studies.

In section 6.5, we conduct an analysis of the COM Platform readiness for use in hospitals. The analysis is done element by element of the platform.

Finally, threats to validity are described, along with mitigation strategies, in section 6.6.

6.1 Enterprise Architecture for COM in Value-Based Hospitals

The 5 case studies, from sections 5.2, 5.3, 5.4, 5.5, and 5.6 provide data points showing to what extent our Enterprise Architecture for COM in value-based hospitals meets the evaluation criteria that were identified in section 3.3.1. This is summarized in Table 6-1 Enterprise Architecture for COM in Value-Based Hospitals below.

We have followed 2 approaches for the evaluation:

- An evaluation case study by case study (i.e, column by column): we analyze how well each case study has covered the set of criteria.
- An evaluation criteria by criteria (i.e, row by row): based on how well the 5 case studies have covered each criteria, the last cell on the right of the table gives an assessment of how well the COM Platform has met the criteria. This assessment is then used for the comparison with Related Work, in section 6.3. The grades used are: Not Applicable, Not Addressed, Demonstrated Potential, Partially Addressed, Fully Addressed.

Table 6-1 Enterprise Architecture for COM in Value-Based Hospitals

Criteria	Case Study 1: Cardiac Procedures Service Line Management	Case Study 2: Joint Replacement Service Line Management	Case Study 3: Model-Driven Tools	Case Study 4: Architecture Analysis of COM Platform	Case Study 5: Business Analysis for Hospital Transformation	How well COM Platform meets criteria
End-to-end coverage of services, QoC, compliance with QBP	End-to-end coverage of services	Service Line Management	All COMP Tools			Fully Addressed
	End-to-end Quality of Care	Adverse Event Management for Surgery	All COMP Tools			Partially Addressed
	End-to-end compliance with QBP or Care Pathway	STEMI, NSTEMI Heart Attack, ACS	All COMP Tools	Generalizability to all service lines		Fully Addressed
	Compliance with healthcare frameworks and ontologies	COMF	COMF; HIMMS EMRAM; ICD-9			Demonstrated Potential
Value-based performance mgt	End-to-end financial visibility	weighted case costing of Use Case 3	All COMP Tools		weighted case costing	Partially Addressed
	End-to-end hospital productivity increase				Analysis of improvements; computation of Return on Investment	Partially Addressed
	Opportunity Analysis based on catchment area needs		Engineering tools (Optimization, Simulation, MCDA)			Partially Addressed
	Support of Patient Cohorts and Service Lines	cohort management; service line management	All COMP Tools			Fully Addressed
Integrated solution	Integration (functional, process, transitions)	functional (service mgt, demand & capacity mgt, performance mgt); processes; care transitions	All COMP Tools	mechanisms for functional integration; process integration; coupling of different software design paradigms		Fully Addressed
	Interfaces with existing hospital information systems		HL7 messaging			Demonstrated Potential
Real-time solution	Real-time operations management	real-time business intelligence; real-time patient tracking	All COMP Tools	mechanisms for real- time management; Event-Driven Architecture based on Event models		Fully Addressed

Criteria	Case Study 1: Cardiac Procedures Service Line	Case Study 2: Joint Replacement Service Line	Case Study 3: Model-Driven Tools	Case Study 4: Architecture Analysis of COM Platform	Case Study 5: Business Analysis for Hospital Transformation	How well COM Platform meets criteria
Clinician-friendly solution	Alignment with clinician workflows	clinical processes modeled by Clinicians in Use Case 3	COMP Modeling Tool			Partially Addressed
Transformation to value-based hospital	Support for organizational transformation	from vertical to matrix in Use Case 3	All COMP Tools		RoI supporting the transformation	Partially Addressed
	Support for process transformation	new hip & knee replacement process	All COMP Tools		RoI supporting the transformation	Fully Addressed
Customizable solution	Customizability of COM information system for each hospital	COSS is customizable because models are customizable in Use Case 3	COMP Modeling Tool	Customizability; Generalizability (COSS is supporting new services based on models)		Partially Addressed
Support of COM functions	Support of the main COM functions in a hospital: * Service Line Mgt * Demand & Capacity Mgt * Supply Mgt * Performance Mgt * QoC, Risk, & Safety Mgt * Accounting Mgt * Human Resources Mgt	All COM functions	All COMP Tools	SOAML modeling	Accounting Mgt	Fully Addressed
Support for decision-making	Support for Strategic, Tactical, and Operational decision-making	Strategic, Tactical, Operational Off-line and On-Line	All COMP Tools		Strategic, Tactical, Operational	Partially Addressed
	COM decision support	DSS for Demand & Capacity Mgt; DSS for Full-Capacity Protocol	COSBench Libraries	Model-Based Reasoning; COOM; Blackboard; Knowledge Sources		Partially Addressed
	Predictive Analytics	DSS for Full-Capacity Protocol	COSBench Libraries	Fast Forward Discrete Event Simulation in Surge Protocol DSS		Partially Addressed

6.1.1 Evaluation Case Study by Case Study

Case Study 1:

- The case study has demonstrated the strengths of the COM Enterprise Architecture in: End-to-end coverage of services, QoC, compliance with QBP; Patient-centered Care; Integrated solution; Real-time solution; Support of the main COM functions in a hospital; Support for decision-making.
- The case study did not cover: Value-based performance management; Customizable solution.

Case Study 2:

- The case study has covered several criteria. It demonstrated the strengths of the COM Enterprise Architecture in: End-to-end coverage of services, QoC, compliance with QBP; Patient-centered care; Integrated solution; Real-time solution; Transformation to value-based hospital; Support of COM functions; Support for decision-making.
- The case study did not cover: Clinician-friendly solution.

Case Study 3:

- The focus of the case study is to demonstrate the technical feasibility of modeling and code generation tools for Model-Driven COM. It showed how these tools supported the COM Enterprise Architecture.

Case Study 4:

- The focus of the case study is on the architecture analysis of the COM Platform. It showed its strengths in Customizability, Integration, Real-time management, Support for decision-making.

Case Study 5:

- The case study is focused on the business analysis of the COM Enterprise Architecture, and has demonstrated its strengths in: Value-based performance management; Transformation to value-based hospital; Support for decision-making.

6.1.2 Evaluation Criteria by Criteria

End-to-end coverage of services, QoC, compliance with QBP:

- The COSS provides an end-to-end coverage of clinical services. The COM Models enable the modeling of the end-to-end care process (Process Model) and all the hospital units involved in the care process (Structure model). The models then drive the generation and build of the COSS. The COSS supports the patient flow from one unit to another, and tracks the patient throughout their hospital journey. The COSS fully addressed the criteria.
- The COSS provides end-to-end QoC, by supporting the QoC, Risk, and Safety Management function in the COM Function Table. However, we did not have the time to explore further the Risk and Safety Management aspects. Because of this, the criteria is partially addressed.
- The COSS complies with QBP or Care Pathways: The case studies have shown examples of compliance with Hip & Knee Replacement QBP, and with Acute Coronary Syndrome QBP. The COSS fully addressed the criteria.
- The COSS complies with the HiMMS EMR Adoption Model framework, and with the ICD-9 ontology. We simply demonstrated the potential in Case Study 3.

Value-based performance management:

- End-to-end financial visibility: The use cases 2 and 5 have provided examples of weighted case costing in order to ensure financial viability. The criteria is only partially addressed because we need an actual deployment to be certain.
- End-to-end productivity increase: the Case Study 5 has shown savings coming from productivity increase. The criteria is only partially addressed because we need an actual deployment to be certain.
- Opportunity analysis based on catchment area needs: The COM Platform Engineering Tools (Simulation, Optimization, MCDA) enable to analyze the population management needs of the hospital catchment area in order to identify opportunities for services or service lines required in the future. For instance, based on the demographics (aging of the population in the catchment area) and simulation, the need for a Joint Replacement service line has been identified as a key strategic priority in one hospital. The criteria is only partially addressed because we did not have enough time for further investigation.

Patient-Centered care:

- The COSS is patient-centered. Instead of focusing on assets (bed, equipment) and staff, the COSS is primarily focused on the flow of patient cohorts throughout the hospital, and is capable of correlating the patient location and the step of care in order to infer actions. Most of the DSS reasoning starts from the patient instead of the Clinician. The care processes in the Process Models is driven from the patient viewpoint. The COSS also provides service line management. The COSS fully addressed the criteria.

Integrated solution:

- The COSS is functionally integrated. The Function model covers all the COM Functional Areas, and their interactions. The COSS fully addressed the criteria.
- The COSS supports standard-based HL7 messaging to interface with the hospital information systems. We only demonstrated the potential in Use Case 3 by lack of time.

Real-time solution:

- The COSS supports real-time operations management. It receives events and acts on them in real-time, thus enabling real-time decision-making from the Clinicians. The Real-Time Patient Flow Management DSS, Operational Business Intelligence DSS, Capacity Management DSS, and Full-Capacity Protocol DSS are providing real-time decision-making support. The COSS fully addressed the criteria.

Clinician-friendly solution:

- The COSS is aligned with the Clinician workflows. Complementing the patient-centeredness, the COSS is managing the Clinician tasks according to their workflows, in order to decrease the cognitive load on them. Patient-Centeredness and alignment with Clinician workflows are not incompatible provided the modeling enables such flexibility. The COM Platform includes a BPM engine, a Rules engine, and a CEP engine in order to support such flexibility. The criteria is only partially addressed because we need more Physicians modeling their workflows in order to ascertain full validation.

Transformation to value-based hospital:

- Support for organization transformation: the COMP Views include the Organization View which enables to model the organization current state (for instance: Vertical), and the future state (for instance: Matrix). The Case Study 2 on Joint Replacement Service Line is an example of such organization transformation. The criteria is only partially met because we need more deployment of a Matrix organization in hospitals.
- Support for process transformation: The COSS supports the Process View of the COM Functions Table. The case studies have shown implementations of QBPs and their impact on the service line. The COSS fully addressed the criteria.

Customizable solution:

- The COSS is customizable for each hospital. This is done mostly with the customization of the COM Models. On an on-going basis, these COM Models can be

customized for new clinical services, as the case study has shown. The criteria is only partially addressed because we need more deployment across hospitals.

Support of COM functions:

- The COSS supports all COM functions in a hospital, complying with the COM Functions Table. The criteria is fully addressed.

Support for decision-making:

- Support for Strategic, tactical, and/or operational decision-making: the COSS complies with the COM Functions Table which supports all 3 decision-making level (operational decision-making is split between Off-line and On-line)
- The COSS provides COM decision support with the 5 DSS:
 - Real-Time Patient Flow Management DSS
 - Operational Business Intelligence DSS
 - Demand Management DSS
 - Capacity Management DSS
 - Full-Capacity Protocol DSS
- The COSS supports Predictive Analytics in the Full-Capacity Protocol DSS: the Fast-Forward Discrete Event Simulation module enables to predict what the patient flows are going to be in the next 4, 8, 12, 24 hours, and simulate “what-if” scenarios in order to facilitate decision-making.
- The 3 criteria above are only partially addressed by the COM Enterprise Architecture because we need DSS deployment in hospitals. The technical feasibility of the blackboard approach is certain. What is unknown is the DSS efficiency in supporting real-time decision-making at the point-of-care.

6.2 Tools Support for Model-Driven COM in Value-Based Hospitals

The hospital transformation is driven by the COM Models which describe the Organization Redesign, the Process Redesign, and the Information System Redesign. This provides a methodology and structure to the hospital transformation. This guides the transformation in a holistic manner, instead of by silos. This guides the transformation in a systematic and comprehensive way, instead of being done in an ad hoc way.

This validation analysis relates to the Model-Driven Engineering approach. The 5 case studies, from sections 5.2, 5.3, 5.4, 5.5, and 5.6, provide data points showing to what extent the Model-Driven tools (COMP Tools and COSBench) support for COM in Value-Based Hospitals meets the evaluation criteria that were identified in section 3.3.2. This is summarized in Table 6-2 Tools Support for Model-Driven COM in Value-Based Hospitals.

We have followed 2 approaches for the evaluation:

- An evaluation case study by case study (i.e, column by column): we analyze how well each case study has covered the set of criteria.
- An evaluation criteria by criteria (i.e, row by row): based on how well the 5 case studies have covered each criteria, the last cell on the right of the table gives an assessment of how well the COM Platform has met the criteria. This assessment is then used for the comparison with Related Work, in section 6.3. The grades used are: Not Applicable, Not Addressed, Demonstrated Potential, Partially Addressed, Fully Addressed.

Table 6-2 Tools Support for Model-Driven COM in Value-Based Hospitals

Criteria		Case Study 1: Cardiac Procedures Service Line	Case Study 2: Joint Replacement Service Line	Case Study 3: Model-Driven Tools	Case Study 4: Architecture Analysis of COM Platform	Case Study 5: Business Analysis for Hospital Transformation	How well COM Platform meets criteria
Domain-specific, customizable models	Domain-specific models for entire hospital	COM Models; UML/BPMN/DMN models	COM Models; UML/BPMN/DMN models	All COMP Tools	Generalizability to all hospital types		Fully Addressed
	Customizability of models for each hospital	Models customizable for each hospital	Models customizable for each hospital	All COMP Tools	Customizability; Separation of Concerns		Partially Addressed
Modeling by Clinicians	Clinician-friendly models		COM Models built/edited by Physicians in Use Case 3	COMP Modeling Tool	Separation of Concerns		Demonstrated Potential
Leverage existing standards & tools	Compliance with modeling standards	UML, BPMN, DMN Yes: all 3 levels	UML, BPMN, DMN Yes: all 3 levels	All COMP Tools	Design decision		Fully Addressed
	Synergy Between MDE and TOGAF Enterprise Architecture			All COMP Tools; COSBench	MDE; TOGAF		Fully Addressed
	Compatibility with modeling tools			COMP Modeling Tool is based on Eclipse Papyrus, Modelio, DROOLS, Camunda	Design decision		Fully Addressed
Enabler for decision support Integrated tool suite	Enabler for COM Decision Support Systems	COOM; Blackboard; Knowledge Sources	COOM; Blackboard; Knowledge Sources	COSBench	Model-Based Reasoning		Partially Addressed
	Integrated tool suite			Yes	Design decision		Fully Addressed
	Weaving of models of different types		BPMN and DMN models woven into UML models in Use Case 3	COMP Modeling Tool	Model Weaving by Design		Partially Addressed
	Code generation capabilities			COSBench using Acceleo, Modelio, DROOLS, Camunda	Design decision		Fully Addressed

6.2.1 Evaluation Case Study by Case Study

Case Study 1:

- The case study has shown that the tools have enabled the generation of a COSS based on domain-specific and customizable models, leveraging existing standards and tools, and supporting decision-making.
- The case study did not address the modeling by Physicians, nor the tool integration

Case Study 2:

- The case study is more comprehensive, and has shown in Use case 3 that a Physician trained on COM modeling could produce the models, and the tool integration has enabled him to work with the Analyst and the Software Engineer in building the COSS

Case Study 3:

- This case study is specifically focused on tools, and has shown that they partially or fully address all criteria.

Case Study 4:

- The case study has shown that the architecture of the COM Platform has, by design, supported the tools in partially or fully addressing all criteria.

Case Study 5:

- This case study is focused on business analysis and did not cover tools at all.

6.2.2 Evaluation Criteria by Criteria

Domain-specific, customizable models:

- Domain-specific models for the entire hospital: the COM Models are domain-specific; they are transformed into UML/BPMN/DMN Models which are also domain-specific. The criteria is fully addressed.
- Customizability of models for each hospital: the COM Models are customizable for each hospital; they are transformed into UML/BPMN/DMN Models which are also customizable for each hospital. The criteria is only partially addressed because we need more deployment in hospitals.

Modeling by Clinicians:

- The COM Models can be built/edited by Clinicians, as we have seen in the case studies. The criteria is only partially addressed because we need more Physicians modeling their workflows in order to ascertain full validation

Leverage existing standards & tools:

- Compliance with modeling standards: COMP has been designed as a UML Profile. The other 2 modeling languages are BPMN and DMN, also modeling standards. These 3 modeling standards are necessary and sufficient for the entire modeling of the COM domain. The criteria is fully addressed.
- Support of TOGAF Enterprise Architecture: The COM Models represent the TOGAF Business Layer; the UML/BPMN/DMN Models represent the TOGAF IS Layer; the COSS module architecture represents the TOGAF Technology Layer. The criteria is fully addressed.
- Compatibility with modeling tools: the COMP Modeling Tool is based on Eclipse Papyrus and DROOLS, which are well-established modeling tool suites. The criteria is fully addressed.

Enabler for decision support:

- Enabler for COM DSS: the COMP Platform uses Model-Based Reasoning, with the Blackboard Architecture Pattern. The criteria is only partially addressed because we need more DSS deployment in hospitals.

Integrated tool suite:

- Integrated tool suite: the COMP Tools and COSBench are integrated and provide the end-to-end transformation from COM models to UML/BPMN/DMN models to COSS module code. The criteria is fully addressed.
- Weaving of models of different types: the case studies are describing examples of the weaving of UML, BPMN, and DMN models together. The criteria is only partially addressed because the weaving is done manually, and this could be a challenge for some Analysts and Software Engineers. Future work is planned to automate this as much as possible.
- Code generation capabilities: COSBench is based on Eclipse Acceleo which is a well-established model-to-code transformation tool.

6.3 Comparison against Related work

In Table 6-3 and 6-4 below, we compare our work against the research projects presented in Section 2.6 Related Work: Current Practice (section 2.6.1), the uTwente CHOIR Framework (section 2.6.2), MPOWER for Homecare (section 2.6.3), and DESSCOM for supply chain decision-making (section 2.6.4). The gaps in these related work were identified in section 3.2. The grades used in the comparison are: Not Applicable, Not Addressed, Demonstrated Potential, Partially Addressed, Fully Addressed.

Table 6-3 Comparison against Related Work (EA for COM)

Criteria	Current Practice	uTwente Framework	MPOWER	DESSCOM	Our COM Platform
End-to-end coverage of services, QoC, compliance with QBP	End-to-end coverage of services	Not Addressed	Fully Addressed	Not Applicable	Fully Addressed
	End-to-end Quality of Care	Not Addressed	Fully Addressed	Not Applicable	Partially Addressed
	End-to-end compliance with QBP or Care Pathway	Not Addressed	Not Applicable	Not Applicable	Fully Addressed
	Compliance with healthcare frameworks & ontologies	Partially Addressed	Fully Addressed	Not Applicable	Demonstrated Potential
Value-based performance mgt	End-to-end financial visibility	Partially Addressed	Not Addressed	Not Applicable	Partially Addressed
	End-to-end hospital productivity increase	Fully Addressed	Partially Addressed	Not Applicable	Partially Addressed
Patient-centered care	Opportunity Analysis based on catchment area needs	Not Addressed	Partially Addressed	Not Applicable	Partially Addressed
	Patient-centered care	Partially Addressed	Fully Addressed	Not Applicable	Fully Addressed
Integrated solution	Integration (functional, process, transitions)	Fully Addressed	Fully Addressed	Not Applicable	Fully Addressed
	Interfaces with existing hospital information systems	Partially Addressed	Fully Addressed	Not Applicable	Demonstrated Potential
Real-time solution	Real-time operations management	Fully Addressed	Not Addressed	Not Addressed	Fully Addressed
Clinician-friendly solution	Alignment with clinician workflows	Fully Addressed	Fully Addressed	Not Applicable	Partially Addressed
Value-based COM transformation	Support for organizational transformation	Not Addressed	Not Addressed	Not Addressed	Partially Addressed
	Support for process transformation	Not Addressed	Partially Addressed	Not Addressed	Fully Addressed
	Customizability of COM information system for each hospital	Partially Addressed	Partially Addressed	Not Applicable	Partially Addressed
Support of COM functions	Support for the main COM functions in a hospital:	Partially Addressed	Partially Addressed	Not Applicable	Fully Addressed
	* Service Line Mgt				
	* Demand & Capacity Mgt				
	* Supply Mgt				
	* Performance Mgt				
	* QoC, Risk, & Safety Mgt				
Support for decision-making	* Accounting Mgt				
	* Human Resources Mgt				
	Support for Strategic, Tactical, and/or Operational decision-making	Partially Addressed	Partially Addressed	Fully Addressed	Partially Addressed
	COM decision support	Not Addressed	Not Addressed	Not Applicable	Partially Addressed
	Predictive Analytics	Not Addressed	Not Addressed	Fully Addressed	Partially Addressed

Table 6-4 Comparison against Related Work (Tool Support)

Criteria		Current Practice	uTwente Framework	MPOWER	DESSCOM	Our COM Platform
Domain-specific, customizable models	Domain-specific models for entire hospital	Not Applicable	Partially Addressed	Partially Addressed	Not Applicable	Fully Addressed
	Customizability of models for each hospital	Not Applicable	Partially Addressed	Fully Addressed	Not Applicable	Partially Addressed
	Clinician-friendly models	Not Applicable	Not Addressed	Not Addressed	Not Applicable	Demonstrated Potential
Modeling by Clinicians	Compliance with modeling standards	Not Applicable	Fully Addressed	Fully Addressed	Fully Addressed	Fully Addressed
	Leverage existing standards & tools	Not Applicable	Not Addressed	Not Addressed	Not Addressed	Fully Addressed
	Synergy Between MDE and TOGAF Enterprise Architecture	Not Applicable	Partially Addressed	Fully Addressed	Fully Addressed	Fully Addressed
Enabler for decision support	Compatibility with modeling tools	Not Applicable	Not Addressed	Not Addressed	Fully Addressed	Partially Addressed
	Enabler for COM Decision Support Systems	Not Addressed	Not Addressed	Not Addressed	Fully Addressed	Fully Addressed
	Integrated tool suite	Fully Addressed	Not Addressed	Fully Addressed	Fully Addressed	Fully Addressed
Integrated tool suite (modeling, weaving, code generation)	Weaving of models of different types	Not Applicable	Partially Addressed	Not Addressed	Not Addressed	Partially Addressed
	Code generation capabilities	Not Applicable	Not Addressed	Fully Addressed	Fully Addressed	Fully Addressed

6.3.1 Current Practice

Strengths:

- Current hospital information systems fully address: end-to-end coverage of services, hospital productivity increase, real-time operations, and integration within the Vendor's tool suite.
- They partially address: End-to-end QoC, Value-based performance management, Patient-centered care, Customizable solution, Support of COM Functions, Support for decision-making

Weaknesses:

- Limited end-to-end compliance with QBP or Care Pathways
- Limited support for process management
- The Clinician workflows are not first-entities and cannot be customized. The applications assume hardwired workflows which do not necessarily meet the needs of different hospital types
- Limited support for organizational transformation
- Limited opportunity analysis based on catchment area needs
- Limited Predictive Analytics
- In general, lack of use of a Model-Driven Engineering approach

6.3.2 uTwente CHOIR Framework

Strengths:

- The CHOIR framework is very strong in criteria related to operations management, and in support for Strategic and Tactical decision-making

Weaknesses:

- The CHOIR framework has not been designed to drive the creation of hospital information systems; it is mostly a modeling framework for Operations Management
- It does not cover functional areas like Performance Management, Human Resources Management, and Quality of Care, Risk and Safety Management

6.3.3 MPOWER

Strengths:

- The MPOWER platform is the strongest of Related Work and Current Practice, and partially or fully addressed most of the criteria
- Their focus is Homecare Services

Weaknesses:

- Real-time solution
- Support for decision-making; Enabler for decision support
- Modeling by Clinicians

6.3.4 DESSCOM

Strengths:

- Support for Strategic and Tactical decision-making
- Tools support

Weaknesses:

- No support for real-time operations management
- No support for process management

6.3.5 COM Platform

Strengths:

- The COM Platform is strongest in End-to-end coverage of services, QoC, and compliance with QBP, in Patient-centered Care, in Integrated and Real-time Solution, in the support of COM Functions, in Domain-specific and customizable models, and in leveraging existing standards & tools.
- The COM Platform is strong in Value-based COM transformation because of its support for process transformation, but its capability in supporting organizational transformation has not been proven yet. No Related Work or Current Practice has been proven to fully support organizational transformation because there are not many value-based hospitals. However, the COM Platform is the only solution designed specifically for this purpose.
- Value-based performance management is only “partially addressed”. No Related Work or Current Practice fully addresses this criteria because there are not many value-based hospitals yet. However, the COM Platform is the only solution designed specifically for them.

Weaknesses:

- The Enterprise Architecture areas of simply “demonstrated potential” are Compliance with healthcare frameworks & ontologies, and Interfaces with existing hospital information systems. This is essentially because we did not have the time to validate further.
- A real validation weakness is in Modeling by Clinicians. This is only weakly validated because of the low number of Clinicians who would and could do the modeling. See discussion in section 6.4.3.
- Support for decision-making is only “partially addressed” because the DSS design has not been deployed yet.

6.4 Validation of Hypotheses

In section 1.3 we identified 4 hypotheses we wished to evaluate based on our understanding of the problem illustrated in Figure 1-1 Model-Driven Engineering of COM in value-based hospitals. Based on chapter 4, we now understand the situation in more detail as shown in Figure 6-1 Research Hypotheses. Clinicians use COMP-Tools to create COM Models which are used by COSBench to generate a COSS that can replace or enhance the current IS for COM

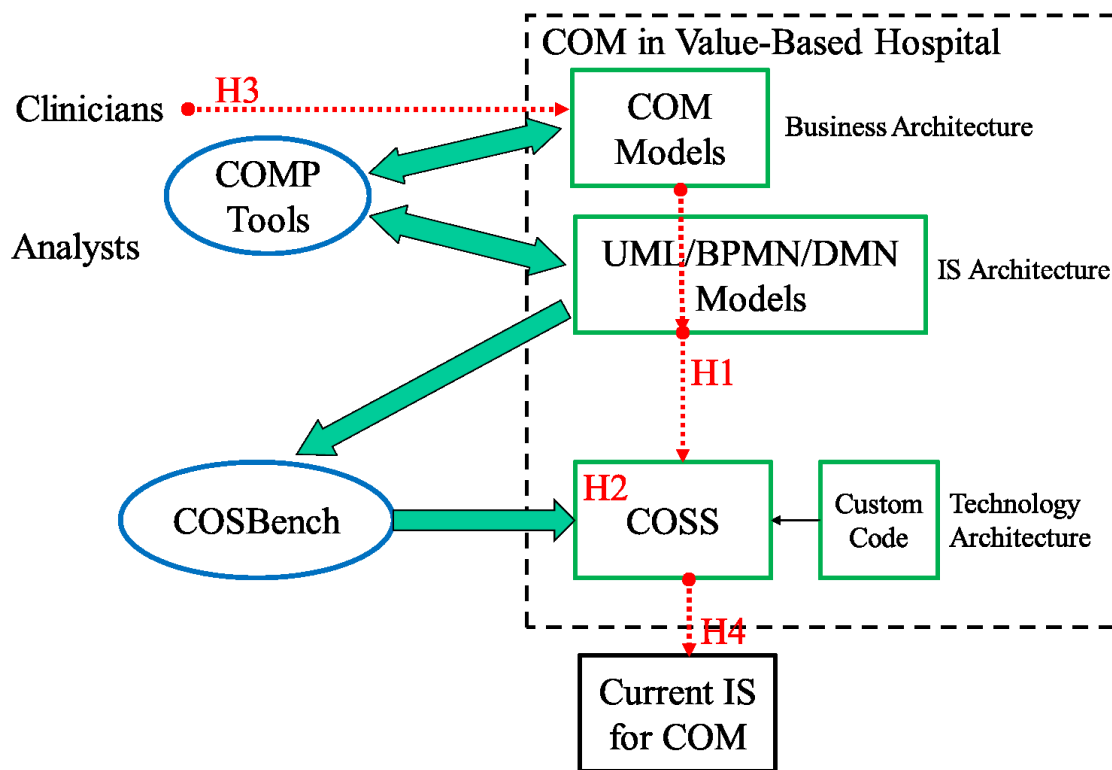


Figure 6-1 Research Hypotheses

6.4.1 Validation of H1

H1: Using Model-Driven Engineering, there is an effective way to build models for Clinical Operations Management in a value-based hospital, which drive the development of customized information systems for end-to-end, real-time, patient-centered clinical service management, in alignment with Clinicians' workflows.

H1 is validated by our case studies in chapter 5 as follows:

- The COSS in the 3rd case study (section 5.4) was directly generated from the COM and UML/BPMN/DMN Models.
- The COSS in the first 2 case studies (sections 5.2 and 5.3) was systematically guided, although manually created, by the COM and UML/BPMN/DMN models.
- The underlying architecture mechanisms of the COSS enable the COSS to support other services or clinical services offered by the hospital (section 5.4.3) than Cardiac Patient Flow Management or Joint Replacement.

Validity Analysis:

- Construct Validity: Based on the Architecture & Design of COMP Tools and COSBench, COM and UML/BPMN/DMN models are based on standards. COSS generation is driven by MDE principles. The use of standards (criterion validity) has been deliberate and systematic (intentional validity). The use of well-established IDE like Eclipse for implementing the COMP Tools and COSBench is a major design decision (representation validity).
- Internal Validity: Based on the COSS Architecture & Design. The MDE principles produce a COSS which meets the validation criteria (sections 6.1 and 6.2). COSS works (prototyping to eliminate major design risks in section 5.4). There are no confounding variables. A possible confounding source of internal invalidity is custom code: mitigation strategy is to document the generic design of COSS module (section 4.7.2), and to keep the custom code to a minimum.
- External Validity: The COM Platform has been validated only in 3 hospitals, because of resource/time constraints. However, using Architectural Inference (section 5.4.3), we can generalize to the entire COM domain (extensions to other hospital services or service lines), and to all Ontario hospitals (each hospital has customized models) because the same architecture, design, and mechanisms are used. However, we understand the generalization argument could be stronger. The mitigation strategy is to continue the Action Research, and validate the COM

Platform with other types of hospitals: rural hospitals, teaching hospitals, tertiary (specialized) hospitals, and ambulatory care hospitals.

- Conclusion Validity: H1 is partially validated, with a mitigation strategy.

6.4.2 Validation of H2

H2: Using a Blackboard Architecture Pattern, there is an effective way to build Decision Support Services for Clinical Operations Management in a value-based hospital, which meet the above clinical service management criteria.

The validation of H2 is validated by our case studies in chapter 5 as follows:

- The COSS DSS are partially generated from the COM Models per the MDE approach (section 5.4), and include Libraries implementing the core functionality.
- The remaining point to validate is whether the approach is effective. The Full-Capacity Protocol DSS (described in Section 4.7.8) is one piece of evidence. The DSS is designed as a blackboard with Knowledge Sources working in parallel and in real-time to provide recommendations to the Flow Manager when the Full-Capacity Protocol has been activated. This is very hard to achieve without a Blackboard Architecture Pattern. However, it has to be noted that the Full-Capacity Protocol DSS has been validated in the Lab only, and not in real-life because of infrastructure constraints at the hospitals.
- The other 4 DSS are another piece of evidence (section 4.7.5 to 4.7.7); they are less complex than the Full-Capacity Protocol DSS, but they represent different categories of problems where a blackboard is most effective.

Validity Analysis:

- Construct Validity & Internal Validity: same arguments as for the H1 validation
- External Validity: The COSS DSS have been prototyped only in 3 hospitals, because of resource/time constraints; however, there are 5 different DSS (sections 4.7.5 to 4.7.8). Using Architectural Inference (section 5.4.3), we generalize to the

entire COM domain (extensions to other services or service lines), and to all Ontario hospitals (each hospital has customized models) because the same architecture, design, and mechanisms are used. However, we understand the generalization argument could be stronger. The mitigation strategy is to continue the Action Research, and validate the COM Platform with other types of hospitals: rural hospitals, teaching hospitals, tertiary (specialized) hospitals, and ambulatory care hospitals.

- Conclusion Validity: H2 is partially validated, with a mitigation strategy.

6.4.3 Validation of H3

H3: The Clinicians, with help from Health Informatics Analysts, and with appropriate training and tools, can build themselves the COM models.

H3 is validated by our case studies in chapter 5 as follows.

At all hospitals, we have met with Nurses, Physicians, and Managers/Directors to train them on the modeling and support them during value stream mapping sessions.

The Clinicians are customizing the COM Models for their hospital. They are used to deal with IF THEN ELSE rules because this is engrained in their medical training. Many Clinicians are trained on LEAN techniques because of care redesign initiatives already under way in many hospitals; therefore, they are comfortable with value stream mapping, and hence with process modeling. The real unknown for them is the use of UML. We are lowering the cognitive load on them as much as possible with the COMP language which is domain-specific, and being a UML Profile, it hides some of the UML intricacies. We are also providing them with Model Libraries that they only have to modify.

We did a survey, described in Section 5.2.6, at one hospital to assess the Clinicians perception on COM technologies (modeling was part of the survey). A large majority of Clinicians were comfortable with the approach, and would like to see the technologies deployed in a 2-3 year horizon.

Validity Analysis:

- **Construct and Internal Validity:** The model customization required for one entire hospital could be done by a small team of 3/4 Clinicians only. 6 Clinicians have been trained at the 3 hospitals, and a large number of Clinicians have been trained on LEAN, at the Yellow Belt level, and are able to undertake process modeling. These Clinicians are motivated and engaged to drive the hospital transformation, and are confident to adapt/modify the models available in the COM Platform in order to customize them for their hospital.
- **External Validity:** The pool of Clinicians trained on COM Models is small. The threat to external validity is high. A mitigation strategy is to rapidly train more hospital Clinicians on modeling, and to provide a COM course at Universities in Business School, Faculty of Medicine, School of Nursing, and School of Engineering. This is part of future work.
- **Conclusion Validity:** H3 is only weakly validated, with a mitigation strategy. A threat to Conclusion Validity is the researcher bias: the survey in section 5.2.6 might have been positive because the Clinicians wanted to support my research. A mitigation strategy will be to have the Clinicians handle the modeling on their own at another hospital, without my involvement. This is part of future work.

6.4.4 Validation of H4

H4: The information systems created per the above approach provide better support to Clinical Operations Management in value-based hospitals compared to the current ones, per the above clinical service management criteria.

H4 is partially validated by the comparison in section 6.3 of our COM Platform against Current Practice and against related work. However, there is a threat to the Conclusion Validity of H4: because I am doing the validation against the existing Current Practice,

there is always a risk of Researcher Bias. As a mitigation strategy, future work will include a validation against other products done by the hospitals themselves.

6.5 Readiness for Use at Hospitals

Table 6-5 summarizes our analysis of the COM Platform readiness for use in hospitals.

Table 6-5 COM Platform Readiness for Use

Level of Readiness	Definition	Model Support	Transformation	Validation	Recommendation to Use
Artifacts					
COMF Functions Table	Table	Table	Manual	Use Cases	ready to be used
COMP & MetaModel	COMP is under-defined	UML Profile	Manual	Use Cases	work in progress
COMP Modeling Tool	COMP & MetaModel	COMP & MetaModel	Manual	Use Cases	ready to be used
COM Models	COMP & MetaModel	COMP & MetaModel	COMP to UML/BPMN/DMN	Use Cases	ready to be used
UML/BPMN/DMN Models	UML/BPMN/DMN	Transformation from COMP	UML/BPMN/DMN to Java	Use Cases	ready to be used
COSBench		UML/BPMN/DMN	Automated	Choice of tools	not yet ready for use
COSS Architecture	COSS Arch Diagram	UML Components	Compilation	Use Cases	not yet ready for use
COSS (non-DSS)	COSS Arch Diagram	COSS Architecture	Not Applicable	No complete prototype	not yet ready for use
COSS DSS	DSS Blackboard	DSS Blackboard	Not Applicable	No complete prototype	not yet ready for use
Grade:					
	ready to be used				
	work in progress				
	not yet ready for use				

Our recommendation is for hospitals to start using the COMP Tools in order to guide their analysis of the hospital transformation towards value-based hospital, and to

document it. This will enable the training of Clinicians and Analysts in COM Modeling. This will also contribute to improving the COM Platform by confronting it with the reality of hospital needs for their transformation.

COSBench and the COSS are not ready yet for use by hospitals. Even though DROOLS has committed to support DMN, it is not released yet and therefore, there is not a single tool supporting UML, BPMN, and DMN modeling all together, capable of code generation or model interpretation. Our design of the COSS DSS is not complete yet, and we have not been able to build a complete COSS prototype and validate it. This is a task for a large team. Our forecast is that it will take 2 years for a team to come up with an industrial-grade COM Platform, enabling the COSS generation to meet the specific needs of each hospital in their transformation to value-based hospital.

In the meantime, the hospitals could start the COM modeling of their transformation, analyze, document, and pilot (without COSS support).

6.6 Threats to Validity

The thesis validation analysis of sections 6.1 to 6.5 has shown 4 types of threats:

- The Research Question is validated with only 3 hospitals. This is a threat to External Validity about the generalization to all Ontario hospitals (and beyond). However:
 - The 3 hospitals are most typical of Ontario hospitals: secondary hospitals with 200-300 beds, offering all services with all units found in most mid-size regional hospitals. All hospitals are implementing QBPs and are driven by their Ministry of Health to transform themselves towards value-based hospital.
 - We knew the threat to External Validity from the beginning and accepted it. The broad scope of the Research Question has been maintained all along because the threat to External Validity will be addressed in future work. The thesis is also the foundation for a “Blueprint for the Model-Driven Transformation of Ontario Hospitals towards value-based hospitals” planned

in the future work, which is proposing a plan for scaling up the deployment of the COM Platform across Ontario hospitals.

- The validation analysis has shown that there is a need for more validation about Clinicians building COM Models by themselves; this is a threat to Conclusion Validity. The mitigation strategy is formal training on COM delivered to the hospital Clinicians.
- The validation analysis has also shown a risk of Researcher Bias; this is another threat to Conclusion Validity. The mitigation strategy is to involve others in the deployment and evolution of the COM Platform.
- The COM Platform is not complete yet, and this is a threat to Internal Validity. COMP as a domain-specific modeling language, is still under-defined; some work remains to make it more formal and complete in terms of model relationships, attributes, and operations. COSBench is not mature yet, and the COSS validation is insufficient. There is a need for increased automation. This will be done as Future Work (see section 7.2).

7 Conclusions and Future Work

7.1 Conclusions

7.1.1 Answer to Research Question, Contributions, and Hypotheses

Research Question: Can we use Model-Driven Engineering to provide better Information System support for COM in a value-based hospital, with a coverage of clinical services which is customized for each hospital, end-to-end, real-time, patient-centered, aligned with the clinician workflows, and based on models defined by the Clinicians themselves? What would an Enterprise Architecture for Model-Driven COM in value-based hospitals be?

Answer: Yes, MDE can provide better information support for COM in a value-based hospital, and the Enterprise Architecture for Model-Driven COM in value-based hospitals, as described in the COM Platform, is the contribution of this thesis.

- A first contribution is an Enterprise Architecture for Model-Driven COM in Value-Based Hospitals, composed of COM Models, UML/BPMN/DMN Models, and the COSS architecture and design.
- A second contribution is the design of a set of domain-specific tools, the COMP Tools and COSBench, which support Model-Driven COM in Value-Based Hospitals
- Finally, a third contribution is examples of COM Models for Joint Replacement service line and for Cardiac Procedures service line, and design examples of COSS DSS for real-time patient flow management, operational business intelligence, full-capacity protocol, demand management, and capacity management.

Hypotheses:

- H1 is partially validated, with a mitigation strategy
- H2 is partially validated, with a mitigation strategy

- H3 is only weakly validated; the main risk is Researcher Bias
- H4 is partially validated, with a mitigation strategy

It was clear from the beginning that the scope of the thesis is big and ambitious, and I accepted this risk. The work done provides some guidance for Future Work to a research team.

7.1.2 Benefits of Model-Driven COM in value-based Hospitals

1) The hospital transformation towards a value-based hospital is facilitated and done in a more systematic, holistic, and effective manner.

One benefit of Model-Driven Transformation is the customizability of the COSS by the Clinicians themselves: more precise, robust, maintainable customizability than what current information systems could do.

Another benefit is the ability to optimize, simulate, and assess the Transformation before actually implementing it.

The same Clinician-driven Models are used for Organization redesign, Process redesign, and IS redesign. This means less training required, and increased Clinicians' involvement in the Transformation.

The Blackboard Architectural Pattern enables the COSS modules, which are generated from the COM Models, to use these same models to reason, that is make inferences about what to do, when, where, and how. Together, MDE and Blackboard are particularly adapted to hospital clinical operations. Each hospital works quite differently from the others, and requires a significant amount of customization to any clinical information system it acquires. However, the knowledge about a hospital clinical operations can be transferrable provided the knowledge engineering has been done appropriately (i.e, captured in the COM Models, separately from the COSS code), with a clear separation of concerns. This knowledge has then been translated into the design of COMP and COSBench in order to become actionable.

2) The hospital operational performance is continuously improved at a lower cost.

As seen in the Section 5.6 case study, some tangible gains in operational performance can be achieved with the Model-Driven Transformation using the COM Platform. Because the COM Models for the hospital can be easily refined over time to continuously support the changing needs, these gains can be sustained and the improvements become continuous. With the gains, savings are generated which could be invested in further improvements.

7.1.3 Limitations of our work

There are several limitations in our work, due mainly to the magnitude of the task:

- A threat to external validity: the work has been validated at only 3 large community hospitals; there is a need to expand the validation to other types of hospitals.
- Two threats to Conclusion Validity. First, there is a need for more validation about Clinicians being able to build COM Models by themselves; the mitigation strategy is formal training on COM delivered to hospital Clinicians. The second threat is the risk of Researcher Bias; the mitigation strategy is to involve others in the deployment of the COM Platform.
- A complete COSS, with the COSBench Libraries, has not been generated yet because of the magnitude of the task, even with tools like COSBench. This should be undertaken by a research team as future work.
- A threat to Internal Validity: COMP is still under-defined, as a domain-specific modeling language. Relationships, Attributes, and Operations have to be added. This is best done jointly with the Clinicians doing real-life COM modeling for their hospital.
- An assumption made in the thesis is that Model-Driven COM for value-based hospitals is best undertaken in hospitals having reached the level 3 of the HiMMS EMR Adoption Model; that is hospitals who already have an EMR and some basic

software applications. The COSS could then be designed as an overlay information system, communicating with the existing systems.

7.1.4 Implications of Model-Driven COM in value-based hospitals

- COM Models put transformation leadership in the hands of Clinicians rather than Administrative personnel. A new generation of Executives will emerge, coming from Physicians and Nurses, trained in Hospital Operations Management. A new Senior Leadership position could be created: the Chief Transformation Officer, in charge of driving the hospital transformation towards value-based hospital.
- Based on the customizability brought by the COM Platform, each hospital could have a COSS tailored to their specific needs.
- There could be a COM Center in each hospital, where clinical operations will be provisioned, managed, and monitored. This is a concept similar to the Network Operations Center of Telecommunications Service Providers, where their entire network is centrally managed.
- Because the COSS could be more easily modified, adapted, and improved, the hospital could become a continuously learning organization; this is the vision of the Institute of Medicine [IOM2012].
- There is a need for COM training programs in universities, ideally in the faculties of Medicine, Nursing, Business, and Engineering.
- Ontario hospitals are spending hundreds of millions of dollars per year on their information systems, buying from Software Vendors. There is a business opportunity for Open Source software. In other industries, it has been proven to be as good as commercial information systems, at a fraction of the price. In the EMR space, there is the example of OSCAR, an open source EMR. Open source COSS could integrate with OSCAR in order to deliver a complete solution to hospitals.
- The delivery of open source hospital EMR and COSS could be done by Software Ecosystems for value-based hospitals, composed of Academia, Hospitals, Startups,

with leadership from one MOHLTC Agency (Canadian Foundation for Healthcare Improvement, for instance).

7.1.5 Lessons learned from thesis research

These are personal and subjective, but could benefit others:

- Power of Action Research: Collaboration between universities and hospitals is paramount for COM.
- Power of Open Source software (like Eclipse, on which COSBench is based). Information Systems in Healthcare are over-priced for the value they are delivering. COSS could very well be delivered as a new generation of Open Source information systems. The OSCAR open source EMR has shown the way for such approach.

7.2 Future Work

There are several research projects which can be undertaken as a follow-up of our work to address the thesis limitations.

- More complete definition of COMP.
- Further validation of COM Platform by building a COSS to cover all the functional areas and views of the COM Models. There is a definite need to test the models to the limits (stress load, anomalies, unexpected events), and measure impact on Key Performance Indicators.
- Further validation of the COM Platform at several hospitals of different types: Small Community Hospitals, Large Community Hospitals, Teaching Hospitals, Tertiary Hospitals.
- COSBench Libraries of the DSS for real-time patient flow management, operational business intelligence, full-capacity protocol, demand management, and capacity management.
- Automatic weaving of UML, BPMN, and DMN models. Automation of Traceability.

- Context-Aware COM, using sensor data fusion. This would be the next step building on location-awareness already provided by the RTLS.
- Blueprint for the Model-Driven Transformation of Ontario hospitals towards value-based hospitals. This is a draft proposal to Ontario hospitals and to MOHLTC which could be implemented over 6-8 years across the 155 public hospitals of the province. Agencies like eHealth Ontario, Health Infoway, and the Canadian Foundation for Healthcare Improvement could drive the transformation by supporting the hospitals.

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Appendix A: Examples of COM Functions for hospital units and service lines

The following examples are aligned on the vertical unit organization; they can be combined in order to follow the horizontal service line organization.

A.1 Emergency Department

Strategic

- Regional coverage
- Ambulance districting
- Capacity dimensioning: wait rooms, treatment rooms, emergency wards, staffing, etc
- ED layout

Tactical

- Patient routing: Triage, Fast-Track, CDU, High-Acuity wards, etc
- Admission control/smoothing
- Physician scheduling
- Nursing scheduling

Off-line Operational

- Nursing staffing

On-line Operational

- Ambulance dispatching & routing
- Treatment planning & prioritization; medical directives

- Patient tracking
- Staff re-scheduling
- RTDC
- Full-Capacity Protocol

A.2 Peri-Op and Surgery

Strategic

- Service mix: General Surgery, Orthopaedic, Urology, Ob/Gyn, Plastics, ENT, etc
- Case mix: Decision on QBP/CP (Hip & Knee Replacement; Hip Fracture; Cancer Surgery, etc)
- Capacity dimensioning: open 1 more OR in the Fall/Winter; create 4 additional beds in Surgery, etc

Tactical

- Master Surgery Schedule for the Fall; Assignment of surgeons to OR blocks
- OR and Surgery Nursing schedules for the Fall
- Elective Surgery booking rules (admission control) for the Fall; Wait list management rules

Off-line Operational

- Elective Surgery case booking
- Nursing staffing
- OR block trading among Surgeons

On-line Operational

- Emergency surgery case booking
- Elective surgery case re-booking
- Staffing changes
- Nurse-to-Patient assignment in Surgery ward
- Bed allocation to Patient in Surgery ward
- Transfer scheduling
- Discharge Planning; Discharge roll-out
- RTDC
- Full-Capacity Protocol (elective procedure cancellations; off-servicing;...)

A.3 Medicine

Strategic

- Service mix
- Case mix
- Ward partitioning: med/surg
- Capacity dimensioning: beds, Physicians, Nurses, equipment
- Ward layout, isolation rooms

Tactical

- Temporary bed capacity change for seasonality
- Admission control: static bed reservation, dynamic bed reservation, off-servicing rules from one ward to another
- Hospitalist scheduling
- Nursing scheduling

Off-line Operational

- Elective admission booking
- Nursing staffing

On-line Operational

- Emergency admission handling
- Elective admission re-booking
- Staffing changes
- Nurse-to-Patient assignment
- Bed allocation to Patient
- Transfer scheduling
- Discharge Planning; Discharge roll-out
- RTDC
- Full-Capacity Protocol

A.4 End-to-End Patient Flow Management

Strategic Planning (long-term):

- Regional coverage
- Service mix
- Case mix
- Capacity dimensioning of units
- Facility layout

Tactical Planning (1-12 months):

- Patient routes design
- Capacity allocation (master surgery schedule, bed allocation to units)
- Temporary capacity changes; Unused capacity re-allocation

- Admission control policies
- Wait time/wait list management policies
- Staff shift schedules

Offline Operations (1–4 weeks)

- Staffing (assigning staff to shifts, assigning surgeons to blocks)
- Elective surgery case booking
- Patient appointments

Online Operations (near real-time)

- Staffing changes
- Nurse-to-Patient assignment
- Patient-to-Bed assignment in Inpatient Care
- Patient Tracking
- Surge protocol
- Ambulance dispatching, routing
- Emergency surgery case booking
- Elective surgery case re-booking
- Real-time OR Management
- Transfer scheduling
- Discharge Planning & Roll-out