Location-Aware Business Process Management for Real-time Monitoring of a Cardiac Care Process

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Abstract

Long wait times are a global issue in the Canadian healthcare system. Patient flow management relies on flow managers to manually detect, investigate and mitigate wait time issues. However, existing data that could support this activity is usually not accurate (because of possible human errors), incomplete, late, and scattered across various information systems in a typical hospital. Yet, in the case of cardiac patients, ensuring a prompt, smooth and continuous care delivery becomes extremely important and motivates improvement of data support for patient flow management activities. This paper presents the development of a location-aware business process management system (LA-BPMS) for monitoring a cardiac care delivery process in a hospital and in real-time. The system provides a better visibility of process execution to patient flow managers who can rely on accurate and real-time information about patient process states, as well as wait time measurements to control patient flow efficiently. We show how an intelligent approach of combining location awareness and business process automation allow this to be possible. A real cardiac care process from an Ontario hospital is used as an example.

Keywords: Healthcare, Wait Time Monitoring, Real-Time Location System, Business Process Management, Workflow Automation, Complex Event Processing, Operational Intelligence.

1 Introduction

Today, a high number of Canadian hospitals experience wait times issues on a daily basis, specifically in Emergency Departments. In Ontario, wait times are as high as 14 hours in average for admitted patients [13] whereas in Québec, some hospitals reach average wait times higher than 20 hours [11]. This situation is unacceptable when one understands the huge impact of wait times on hospital quality of care, patient satisfaction and hospital costs, among others [7][14]. That is why wait time has become the Ontario Ministry of Health's top-priority health concern through the *Ontario Wait Times Strategy* program launched in 2008.

Wait time is a patient flow related issue that occurs whenever an activity has to be delayed due to certain contextual conditions preventing its proper execution. Similarly, a *patient wait time* quantifies the occurrence, in the patient experience, of delays in care service delivery. Some factors influencing the occurrences of wait time include resource allocation, patient arrival rate and process performance (e.g., patient discharge rate) [7][8].

In a hospital environment, patient flow management practices involve the monitoring of the patient flow state across an assigned unit and the application of decision actions to mitigate problematic issues where patient flow can be compromised. Such patient flow strategies involve, for example, opening new beds or calling for more staff. Each of these decisions yields different impacts on hospital performance measured along various metrics such as wait time, costs and resource utilization. One reason why current patient flow management does not give satisfactory results is that management strategies (e.g., calling in more staff) are usually applied long after waiting has started and the backlog of patients has considerably grown [7]. The consistency of such ineffective performances indicates shortcomings of existing practices.

While there are many causes of patient wait times, one we are trying to address and focus on is the timely access to required information. It is clear that successful management of patient flow requires management decisions to be made based on a clear and truthful knowledge and understanding of the current state of patient flow in the hospital. Using real-time information, analysis can be proactive and bottlenecks can be identified on time and, in some cases, prevented before they occur. That is the idea addressed by our proposition: the development of a location-aware business process management system to monitor care processes in real-time, as they evolve. A care process defines the coordination of activities and procedures involved in assessing, diagnosing and treating a patient exhibiting a medical condition. For example, for a cardiac patient, activities like triage, consultation or angiogram are parts of the cardiac care process followed by a hospital to ensure appropriate and effective delivery of medical services. Having visibility over the real-time state of the care processes in a given hospital corresponds to identifying the state of each patient being concurrently treated in the hospital. It requires the ability to know, among other things:

- Where are patients physically located in the hospital (e.g., in the triage room, in the consultation room, etc.)?
- In which step of their care process are they (i.e., which care activity are they undergoing)?
- Is there any wait state? In other terms, is the patient waiting for a care activity to occur? If yes, then how long ago has the wait started and why?
- For patients to be admitted, how many beds are available?
- Is there any bottleneck regarding the bed management processes (e.g., bed cleanup, bed assignment, etc.)?

Those are the types of questions asked by flow managers every day. The necessity of having a good visibility of the entire state of the processes they manage is crucial. This requires the ability to know the state of their patients in the hospital and, if there is any flow issue at any given point in care, to also be aware of the state of resource (e.g., the number of nurses available) related to that point of care.

In this paper, we propose the development of a *Location-Aware Business Process Management System* (LA-BPMS) to support the real-time access to such information. We show how to enable monitoring of patient care process, but also, the tracking of the location of patients and staff. The monitoring data generated by those two functionalities are then smartly combined in a way which allows the system to infer/induce new valuable information about the state of the patient flow in the hospital. All this information, captured automatically and in real-time in the hospital, is made accessible to hospital flow managers through mobile devices for immediate access. The resulting improved visibility of their processes empowers them to make better and informed decisions to efficiently manage care processes and regulate patient flow. This paper also presents a solution example that specifically targets LA-BPMS support for an end-to-end (from admission to discharge) cardiac care process. A *cardiac care process* is a process that defines the coordination of the activities involved in assessing, diagnosis and treating a patient exhibiting cardiac symptoms.

The remaining sections of this paper are organized as follows: Section 2 reviews the literature on relevant research work conducted with the objective of improving data visibility support in hospitals. Section 3 presents the steps involved in implementing a LA-BPMS for monitoring a cardiac care process. Section 4 presents the results of demonstrations conducted with stakeholders. Section 5 compares our system with existing alternative approaches. Finally, Section 6 concludes this paper by highlighting our contributions and future work.

2 Literature Review

Keyword-based queries were performed on some of the main search scientific search engines (SpringerLink, ACM Digital Library, IEEE Xplore, Google Scholar, ScienceDirect, and Elsevier). Among the numerous papers reviewed on healthcare workflows, location awareness, wait times, and real-time monitoring, 53 were selected for further investigation, but only a handful were specifically relevant to our study. They all aim to provide system solutions to improve data access, task support and data quality in healthcare. Each of those papers targets specific problematic areas of healthcare operations.

The first one by van Hee et al. presents the development of an adaptive workflow management system (WfMS) motivated by the necessity to reduce medical errors and improve quality of care [19]. The authors use workflow nets, a special class of Petri nets to model adaptive workflow processes. The concept of "adaptive" refers here to the ability of the process to modify itself on the fly. This flexibility attribute is stressed as a requirement for dealing with the complexity of care processes. The WfMS is designed to enhance staff collaboration and access to relevant patient-related information in comparison to traditional data-centric and scattered Hospital Information System (HIS) infrastructure. The patient gets updates with personalized medical information pertaining to the current state and evolution of his/her process (ongoing treatments, expectation, and risks). The approach aims to improve process transparency and patient care experience. The paper simply proposes a "process-centered patient centered framework for a new generation of HIS".

The second research by Zhang et al. presents a workflow-based Radiology Information System (RIS) [21]. The goal is to provide a system that allows monitoring, in real-time, the state of radiology workflows. This is an integrated process view that employs dashboards to help radiology administrators visualize information representing the workflow states of their processes. The authors discuss workflow modeling and implementation using a system based on YAWL (Yet Another Workflow Language). Zhang et al. also present an architecture that uses an adapter service to interface and synchronize the new process-oriented system with the underlying legacy data-driven radiology systems. The end-user dashboard focuses on reflecting the information about the state of current processes and some key radiology workflow metrics such as examination turnaround time, report turnaround time but also, wait times.

The third research, conducted by Poulymenopoulou et al., presents the development of a cloud-based Emergency Medical System (EMS) [10]. The authors are interested in a support system that brings together the individual and distributed activities involved in emergency care processes, hence providing collaborative and orchestrated "access to patient and operational information regardless of location and time". Given the nature of such a ubiquitous and trans-institutional system, the authors identify specific challenges related to the use of a common information exchange format between different healthcare systems. They present an architecture that combines a workflow module containing a process aggregator, a messaging system for system interoperability (mainly interfacing existing medical systems), a mobile application for user task completion, a security module and a cloud-based database module hosting all system information including XML-based emergency care information and system definition files.

None of these approaches really exploits location awareness for the real-time monitoring of patient flows, which would enable better decision making. A more detailed comparison with our own work will be presented in Section 5.

3 LA-BPMS Development

This section presents the work involved in the development of a LA-BPMS. It also demonstrates how the value of real-time monitoring of process performance is achieved. Before getting into the core elements of the system, a specific cardiac care process is presented to concretely illustrate the approach used in the development of our system.

3.1 Cardiac Care Process Example

This section presents the cardiac care process used as an example throughout this paper. Process information was gathered from hospital clinical pathways and interviews with clinical flow experts. *Clinical pathways* are care management tools containing standardized guidelines (necessary activities, their sequence and their goals) for evidence-based healthcare [6]. They are used here as the "backbone" of the care process models. Their popular adoption by hospitals can be explained by the fact that clinical pathways help reduce variability in patient care, decrease resource utilization and improve quality of care delivery [6][18]. The complete cardiac care process takes place across various hospital departments: Emergency Department (ED), Cardiac Care Unit (CCU), Cardiology Ward (CW), Cardiac Catheterization Lab (CCL). This view is illustrated by Figure 1.

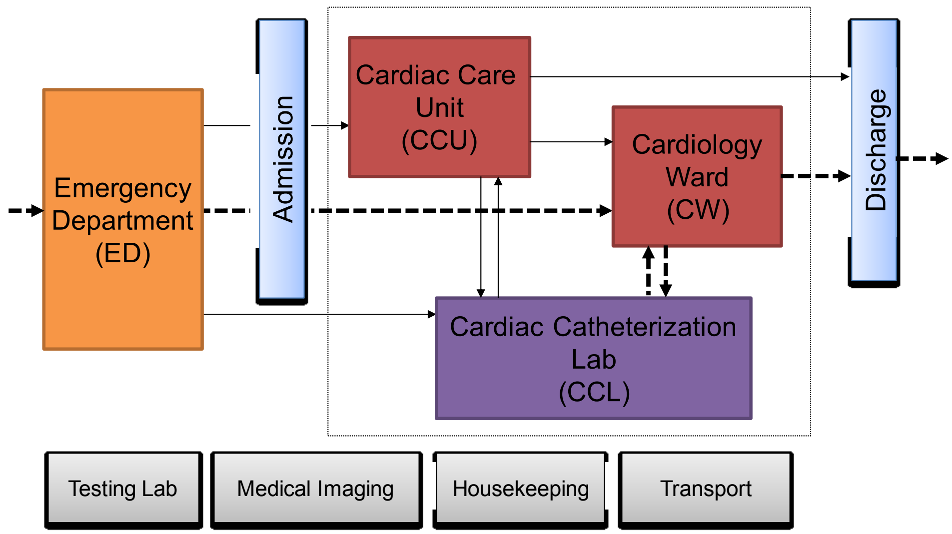

Figure 1 – Cardiac Patient Flow across Hospital Units

The arrows on the diagram indicate the usual possible flows of patients from one unit to another. The interrupted arrows indicate the possible paths that were considered for our work. Note that "Admission" and "Discharge" represent respectively the patient admission and the discharge areas. "Testing lab", "Medical Imaging", House-Keeping" and "Transport" are ancillary processes and are also involved and considered in our cardiac care process case study.

The following realistic scenario depicts the main activities and steps involved in the care process used for the design and validation of LA-BPMS (the actors are italicized):

1. *Patient* with cardiac symptoms arrives in ED at 08:45;
2. *Triage Nurse* checks vitals;
3. *Patient* is seen in ED Assessment Room by *Physician* at 08:58, who then orders an Electrocardiogram (ECG) and Blood Test.
4. *Physician* then leaves to visit another patient.
5. *Nurse* does ECG and takes blood sample at 09:10;
6. *Nurse* communicates ECG results to *Physician* at 09:15;
7. *Patient* waits in ED Assessment Room.
8. Blood test results are communicated to *Physician* at 09:35.
9. At 10:15, *Physician* sees *Patient* again; he communicates Diagnosis of Non-ST-Elevation Myocardial Infarction (NSTEMI)
10. *Physician* requests Admission to CW and writes referral for angiogram and eventual PCI, at 10:25
11. Response to CW bed request at 10:26: No bed available for now. (The current patient will have to wait for a patient occupying a bed in the CW unit to be discharged and for that bed to be cleaned up)
12. Response to referral at 10:40: *Patient* is scheduled for angiogram next day at 11:00
13. *Patient* is given medication by *Nurse* while in ED Assessment Room, per Acute Coronary Syndrome (ACS) Clinical Pathway - Day of Admission;
14. *Another Patient* in CW bed 106 is discharged at 16:30
15. *Housekeeping* is informed at 16:35, and comes in to clean bed at 17:00
16. Bed/Room is cleaned up at 17:45, and *Admission* is informed at 17:50
17. CW bed 106 becomes available and assigned to *Patient* at 18:15
18. *Patient* is transported to CW at 18:35
19. *Patient* arrives in CW bed 106 at 18:40
20. *Patient* keeps getting care per ACS Clinical Pathway – Day of Admission
21. Next morning, *Patient* gets care per ACS Clinical Pathway – Day 1, which is also Intervention Day
22. *Patient* is called to CCL at 10:30

23. *Patient* is transported to CCU, and is prepared for procedure
24. Angiogram, followed by same-sitting PCI, is started in CCL at 11:40
25. *Patient* is sent back to CCU at 12:30 for post-procedure monitoring
26. Procedure is deemed to be successfully completed at 16:00, and *Patient* can leave CCU
27. *Patient* is transported back to CW at 16:20
28. *Patient* keeps getting care per ACS Clinical Pathway – Intervention Day
29. Next morning, during 08:30 round, *Physician* sees that *Patient* is recovering well and decides to discharge him
30. *Discharge Nurse* schedules *Patient* for 11:00 and goes through the checklist per ACS Clinical Pathway – Discharge Day
31. *Patient* leaves his bed in CW at 12:40, and is picked up by his family
32. *Housekeeping* is informed at 12:45, and comes in to clean bed at 1:30
33. Bed/Room is cleaned up at 2:00, and Admission is informed at 2:10
34. Bed is assigned to a *New Patient* at 2:50"

3.2 Care Process Automation

The presented scenario is now used to construct representative business process models using the Business Process Model and Notation (BPMN 2.0). BPMN is a graphical notation for specifying models for business processes [12]. BPMN was chosen because of its intuitiveness, the richness of its constructs to model complex processes and its wide adoption in many industries. Despite the strengths of the notation, various modeling challenges arise due to the significant human component involved in healthcare processes [4]. This becomes more problematic when dealing with complex processes. At that point, effective process support requires the development of flexible-enough process models that can handle the variability of model expression. Much work has been invested in the development of *flexibility patterns* to solve those issues [16][17]. For example, for a simple case where a nurse needs to execute an ECG and a blood test on a cardiac patient, no specific order (to complete them) is usually prescribed and the nurse could follow any sequence depending on the context. This situation can be handled by recognizing that it corresponds to the *parallelism* flexibility pattern [17][20]. This pattern can be implemented in BPMN using an AND-gateway, as illustrated in Figure 2.

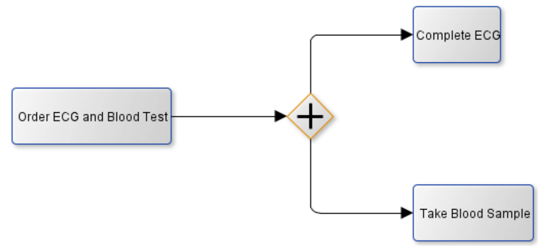

Figure 2 – Illustration of Parallelism in BPMN

Many other BPMN design patterns have been developed to cover different modeling issues such as synchronisation, choice, multiple instances, interleaving, and cancellation [20]. However, flexibility can usually compromise size and maintainability of the process models. The *subprocess* BPMN language construct can be used as a multi-level structuring and information hiding mechanism to ease management of model's size and complexity, and improve process readability and understanding [15].

With the developed process models, a BPMS is employed to enable process automation. In order to achieve this, process models need to be transformed into implementation "models" executable by the Business Process Management (BPM) engine. That is, process models are augmented, using the BPMS, with programmatic details such as: implementation service for each process activity, computer user accounts for roles, access management to activities and information, definition of data inputs and outputs for activities, and flow routing for message events.

Three main types of services were implemented according to the process activity: user interfaces for user tasks, integration services (mostly web service calls to interoperable systems such as other system modules or hospital information systems) and general services (local processing). This process-aware implementation can then be deployed inside the BPM engine and made available to process actors (primarily physicians, nurses and flow managers). Figure 3 presents an extract from one of our process models designed following the cardiac *clinical pathway*. This process was first designed informally by senior nurses in an Ontario community hospital, and then refined to embed communication with external systems, data models and user interfaces.

Role support involves the development of user groups for process actors and their mapping to existing process user accounts. Finally, the information for data inputs and outputs is extracted from process requirements (clinical pathways, expert interviews). This information is then modeled to represent the business domain objects that are manipulated by the processes; generally, patient care information required for a given task as input, and added-value information produced by the execution of the task as output. Examples of inputs/outputs objects for a physician's initial assessment task in a cardiac care process include:

- Inputs: patient electronic file (with history), information about nurse in charge, current triage score and any nurse comments.
- Outputs: patient physical assessment reported by the physician, physician order list for tests to be conducted on the patient and any additional physician comments.

The deployment of those care process models into a BPM engine enables technological support of patient care activities, hence improving efficiency, system integration, teamwork coordination and cohesion. The full automation of the care process allows staff to complete their tasks using a mobile computer device interacting with the BPM engine.

The BPM engine records information (with timestamps) about each activity undertaken by the actors for each *care process instance* (i.e, corresponding to each patient being treating in the hospital following the hospital cardiac pathway). The engine is also integrated with the existing HIS of the hospital to provide end-to-end flow of information.

Enabling mobility offers the significant advantage of removing the location dependency of staff for data entry tasks. This improves the efficiency of the care process when compared to current practice where, for example, the physician has to login and logout each time to a physical computer desk to reports information about his consultation with the patient. Also, this improves staff communication by enabling the use of a computer messaging solution as opposed to current asynchronous manual calls among staff. As shown in Figure 4, iPad devices running a client application were used to enable mobility and efficient (minimal) user interactions. A conventional Web interface (for personal computers and non-iPad tablets) is also available.

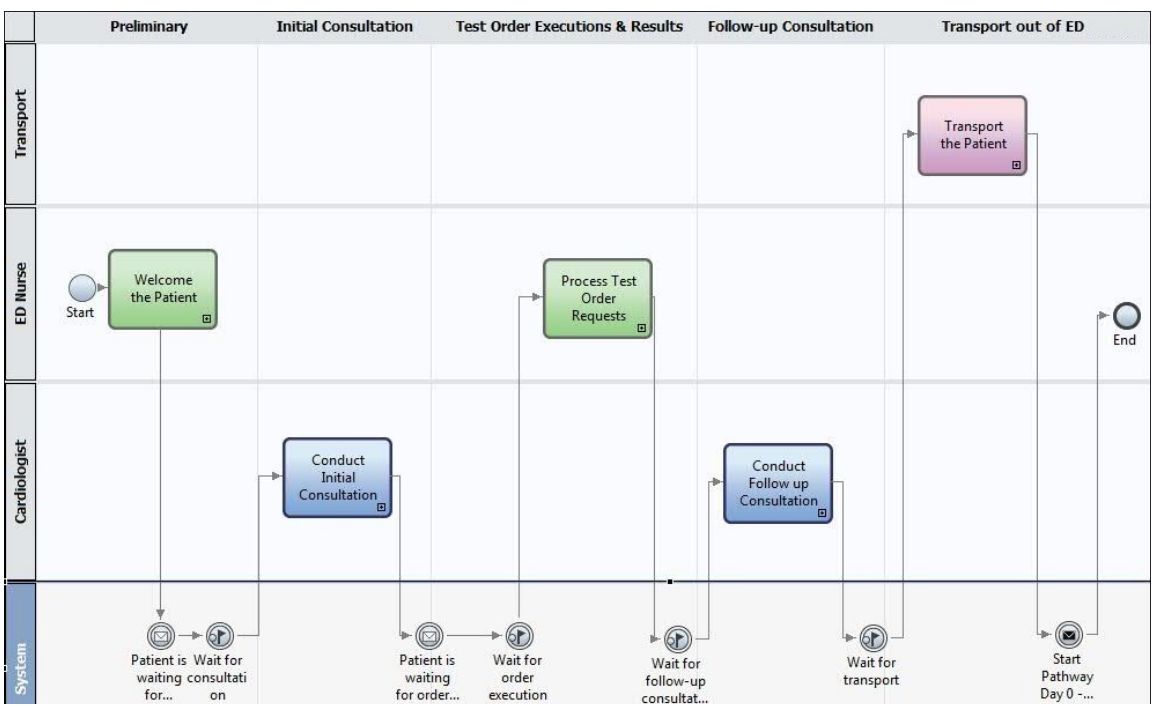

Figure 3 – Sample of ED Process of Cardiac Care (with IBM Business Process Manager)

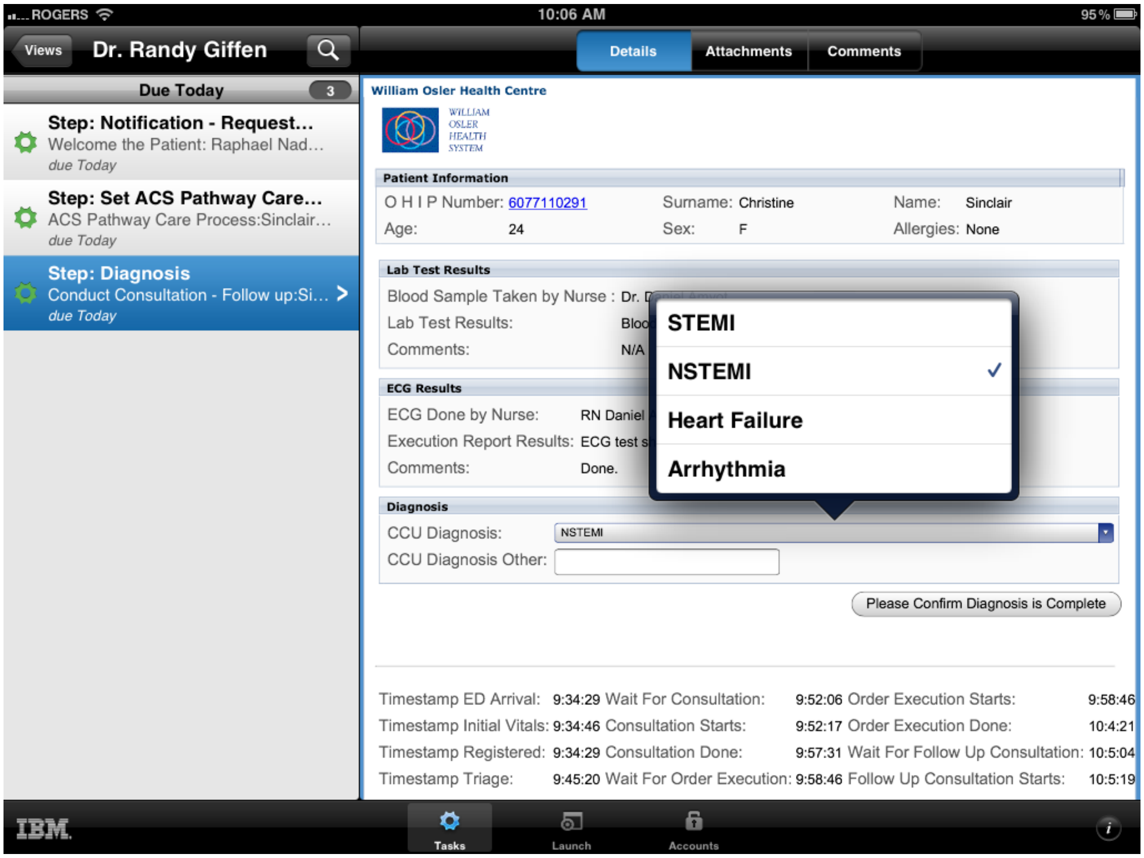

Figure 4 – Apple iPad Client Interface

3.3 Real-time Location Tracking

Process automation provides not only support for existing manual processes but, also, the benefit of monitoring the progress of the care process state by recording process activities. This makes possible real-time updates on process status, as well as measurement and reporting of service times and wait times for care activity. For example, service time for a triage activity is obtained by computing the difference between the timestamp recorded by the BPMS indicating the start of the triage activity and the timestamp indicating its completion. Also, information related to the performance of certain activities is sometimes not granular or detailed enough (e.g., transport of a patient). Visibility can be improved by using location tracking to capture more granular "checkpoints" along the performance line. Those checkpoints can be provided by tracking the location of patients and staff (as shown by the icons in Figure 5) and flagging the spots on the hospital map for which the location information represents high-value knowledge.

In the context of our work, the real-time location system (RTLS) used to capture the location information is needed to accurately infer wait times (in addition to providing actual location of devices, assets and people). For each resource of interest, tags are provided. In order to achieve a 2m to 3m location tracking accuracy (e.g., for a room or a corridor), a RTLS that uses Wi-Fi fingerprinting technology [9][22][23] is preferred, especially in terms of costs and ease of deployment. The active tags receive Wi-Fi signals and send periodic updates and motion updates (whenever the tag moves) for all selected access points to the RTLS server [3]. The server combines trilateration algorithms [5] and fingerprinting data to accurately compute the tags' location. In order to detect operational state and wait state in the patient care process, we are interested in capturing entries in and exits out of *zones* in the hospital.

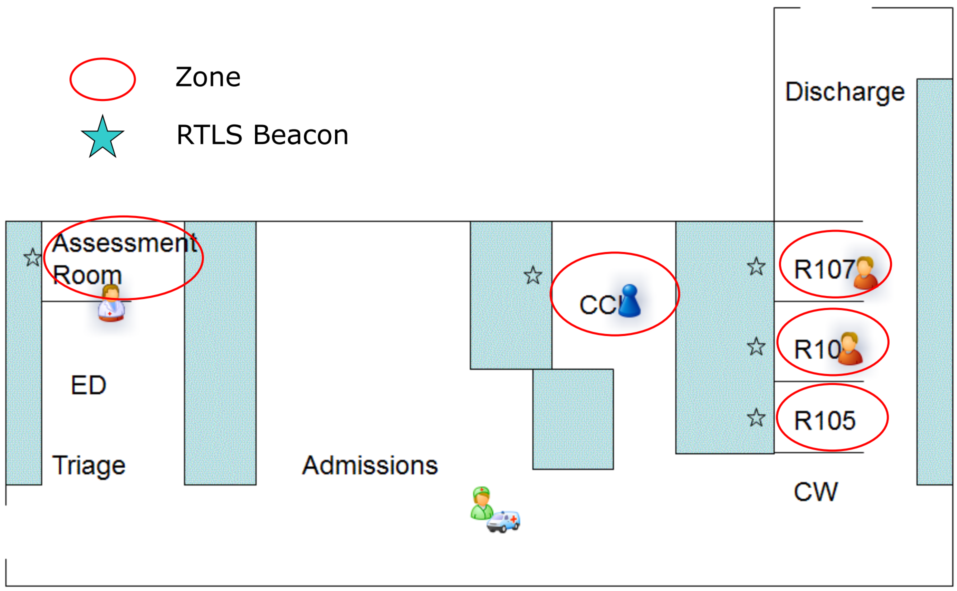

Figure 5 – Location Tracking Map for a Cardiac Process, with Zones and People (with Ekahau)

These zones are often referred to as *choke points* [3]. Zones can be hospital departments, units or even patient rooms. In practice, this level of precision shows to be sufficient for most real-time location tracking scenarios in hospitals. However, for certain use case scenarios where the region is delicate and the successful detection of the tag is critical (at patient's bed site, especially in a multi-bed room), infrared (IR) technology is used. *Beacons* (Figure 5) can be installed (e.g., above beds) to augment the resolution and accuracy of the location detection.

In summary, RTLS combines Wi-Fi and IR location beacons to cover all critical hospital zones (e.g., ED, CW, CCL, etc.) and bed site entrance and exit detection scenarios. We have identified ED, CW, CCL departments as well as CW beds to be the zones involved in our cardiac care scenario. The RTLS generally tracks patients and staff location in the buildings as well as entry and exit events in/from a given zone (e.g., ED unit, bed room of a specific patient).

Most RTLSs feature remote tag management interfaces for tag protection (with automatic alerts), tag configuration, tag battery life and temperature monitoring, etc. Given the particularity of the hospital, new generations of tags designed for healthcare can be disinfected and sterilized to be re-used from discharged patients to new patients. Security mechanisms can easily be put in place to avoid tags to be stolen by, for example, detecting whenever the tag crosses a certain location.

3.4 The Smart Combination: Using Complex Event Processing (CEP)

The fact that we can now automate cardiac care processes and track patient and staff locations in real-time gives us real-time visibility for two types of information:

- The real-time state of the care process (e.g., the patient is being triaged).
- The real-time location of all tracked resources.

The availability of those two streams of information allows us to accurately infer wait times. To better understand how, we have to recall our definition of wait time: A *patient wait time* quantifies the occurrence, in the patient experience, of delays in care service delivery. A delay in care delivery corresponds, for example, to an activity not being able to be completed at the right time, i.e., a situation where the next step in the care process cannot be completed because something is missing or not right. In fact, apart from the orchestration requirement naturally expressed by process logic, a process activity usually requires a specific process context state to be executed. This state can be represented as a set of more or less complex logical conditions on the execution of that activity.

Wait times usually occur in hospitals due to the unavailability of a resource required for the execution activity (equipment or physician missing). The main condition on these resources is usually related to *location dependence*: most patient care activities require the provider to physically be with the patient to administer the care.

This location dependence requirement can be checked in real time, whenever the next activity should execute, by evaluating the location of the corresponding resource (using the RTLS). In the case where the location of the resource/provider does not match the requirement at that specific time, the activity cannot be executed; we can then *securely infer that the patient* ***starts waiting***. Conversely, the patient ***stops waiting*** whenever the condition is validated (e.g., the care provider reaches the patient's room). This gives us as a result the ***wait time interval*** of the patient for that activity.

To automate the detection of such wait times, a *Complex Event Processing* (CEP) engine can be used. Such engine allows us to configure data stream sources (in this case RTLS and BPM) and knowledge inference rules. A knowledge inference rule consists of a triggering event and of inference logic composed of logical conditions, which when evaluated as valid cause the triggering of the corresponding event. For a CEP engine, those logical conditions are evaluated against the growing database of information received from its data stream sources. For example, the inference rule about the fact that a patient is waiting for consultation can be expressed in the following way:

- Premise 1: The next care activity for the patient P1 is a consultation with physician X6.
- Premise 2: Location information of physician X6 does not match the zone Z1 (Z1 being a logical area on the RTLS map identifying patient P1's room).
- Inferred knowledge: The current location of physician X6 does not correspond to the location point required for the location-dependent activity of consultation of patient P1 to take place as the next step in the care process (as required by the implemented clinical pathway). Consequently, the process has to wait for all necessary conditions to be satisfied before execution (notably, the physician must be in the patient's room).
- Generated event: Patient P1 is waiting for consultation (and this complex event is sent back to the BPM).

Note that Premise 1's information is communicated from the BPM source since the latter monitors real-time progress of the care process, whereas Premise 2's information is provided by the RTLS in real-time. The following list presents the major rules that were implemented for monitoring wait times in our cardiac care process:

- Patient wait for Physician Initial Assessment.
- Patient wait for order tests to be done.
- Patient wait for lab results.
- Patient wait for Physician Re-Assessment.
- Patient wait for bed cleanup by housekeeping.
- Patient wait for bed to be assign (wait for bed).
- Patient wait for transport to come.
- Patient wait for CCL procedures (angiogram, PCI).
- Patient wait for discharge.

The satisfaction of a rule triggers the event that informs about wait time start and end for a given care service. The effectiveness of this approach is made possible by a novel combination and flow of information between BPM, RTLS and CEP technologies. The detection of those wait times in real-time can be immediately brought back to access and flow managers, who can then take action upon them while having access to performance records of such information.

3.5 Abstract Architecture

The complete abstract (and largely technology-independent) architecture of our system, which summarizes the ideas presented so far, is shown in Figure 6.

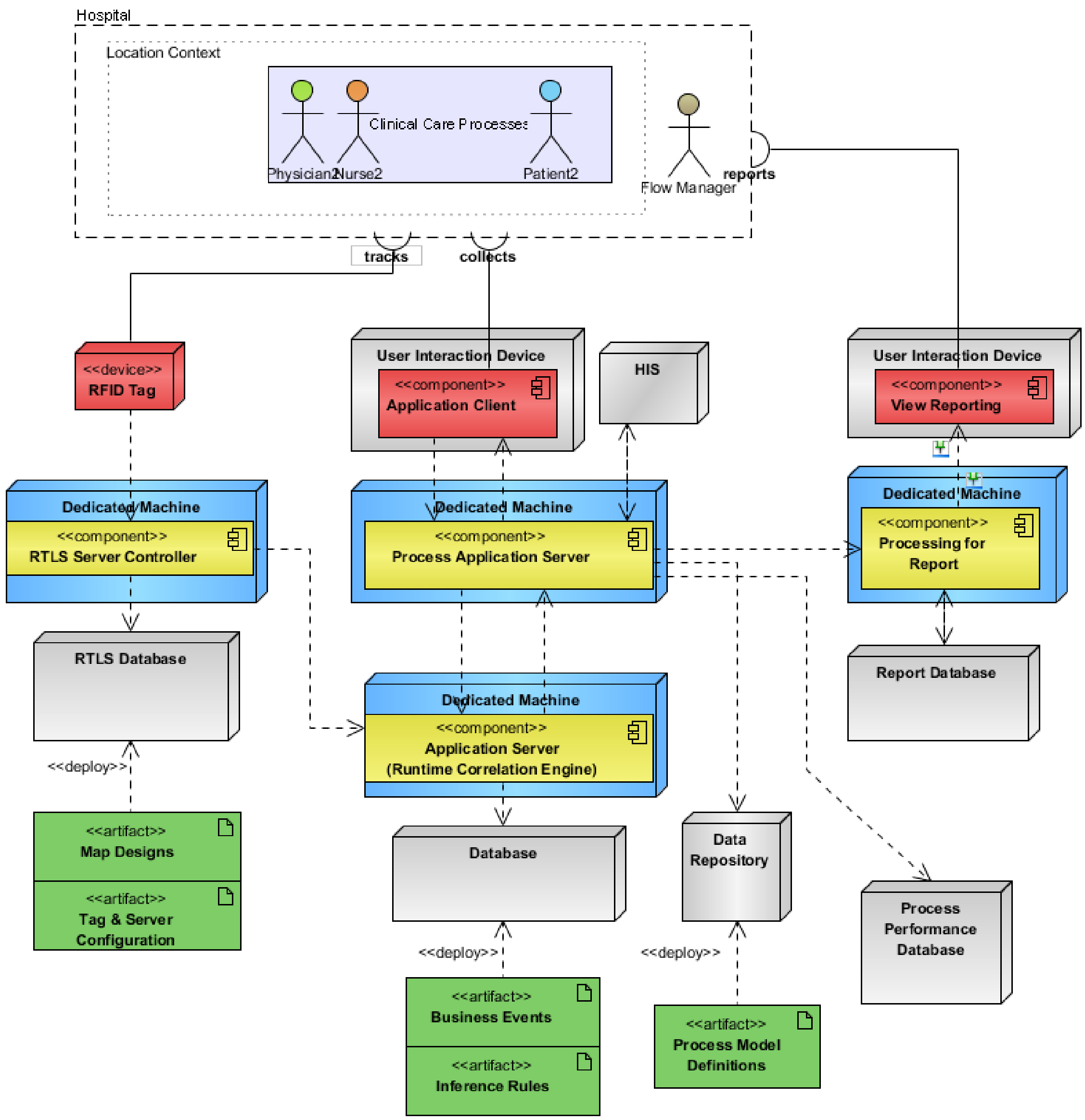

Figure 6 – Abstract LA-BPMS Architecture

In this architecture, the *Process Application Server* is essentially a BPM engine, whereas the *Runtime Correlation Engine* implements complex even processing (CEP) capabilities. The two other main components are an RTLS server, and a reporting component enabling real-time business analytics about patient, bed, and process states. This last component falls outside the scope of the paper but is described in the work of Baffoe et al. [1]. Figure 6 also identifies logical databases and artifacts required for LA-BPMS.

To ensure robustness in a system that likely has to handle a heavy load of events, a messaging system (e.g., IBM Message Broker or Microsoft BizTalk) can be used to interface event communication between the different subsystems involved in the architecture.

The role of the BPM engine is to monitor task completion events and provide process support using automation. All this information is sent to the CEP via a communication mechanism, in our case, web service interoperability. The RTLS engine tracks locations of resources in real-time and also updates their location change relative to the predefined zones of interest. This information is subsequently relayed to CEP through web services as well. Now, CEP computes each new incoming data against its base knowledge of *facts* and *rules* to infer whenever a patient wait state occurs or finishes. Such information is sent back to the BPM engine so it can adapt its flow, as well as to the reporting engine for display to hospital managers.

Web service calls are primarily used to implement an SOA infrastructure, which promotes modularity and low coupling between components of the system.

4 Evaluation

In order to evaluate our idea, a prototype implementation was built following the abstract system architecture of Section 3.5 and covering the cardiac care process presented in Section 3.1.

Two different sets of configurations were developed for two separate physical locations: one for a map located at the University of Ottawa (Figure 5) and another one at William Osler Health Centre in Brampton, Ontario. In both cases, the maps correspond to a single, large room in which we were simulating a complete healthcare complex (hosting the different units from Figure 1: triage, ED, CW, CCL, etc.). Such a setup proved to be a major test ensuring that the solution system is operable in an environment where hospital units are organized as indoor and small open areas (and occasionally beds) separated by tiny spaces. Under such sensible settings, configuration changes on the system regarding, for example, motion sensor of tags and frequency of location updates allow the system to meet the time requirement for detecting wait states and monitor care process operational states as they occur. The system solution was implemented using the following elements and products:

- *IBM Business Process Manager* (BPM): used for process automation and user task support (on mobile devices) and management.
- *Ekahau RTLS*: used for real-time location tracking of patients and staff.
- *IBM Websphere Business Event* (WBE): CEP engine used for the *correlation* of data (process state updates and location updates) from stream sources, to infer wait state.
- *Patient Flow Manager* (PFM): internal Grails and IBM Cognos application built to display real-time patient care process state information and real-time patient states and bed states [1].
- *RTLS Event Dispatcher*: internal Java application using Ekahau' development environment to publish filtered RTLS events to interested third-parties via web service integration.
- *IBM Message Broker*: acting as a broker for events between system components.
- *Apple iPad devices*: to enable mobility in task support and collaboration.

In total, 21 demonstrations of the system were conducted with various stakeholders across the two sites (University of Ottawa and Osler Hospital) between July 2012 and May 2013. Demonstrations were arranged by sessions targeting specific groups. Participants included physicians, nurses, hospital managers, IT staff, and researchers from 3 different hospitals and 2 different universities. They sometimes even played the role of a physician, a nurse, or a patient as part of the demonstrations. Much feedback was collected through a survey involving over 100 participants at Osler, and informally at the University of Ottawa. Session participants were able to acknowledge the capabilities of the system to achieve four major functions:

- The automation of an end-to-end cardiac care process representative of common hospital scenarios.
- The accurate tracking of patient and staff locations in real-time across the hospital.
- The mobile access to operational information for physicians and nurses using iPads, with a particular focus on context-sensitive and relevant information highlighted (to minimize cognitive burden).
- The accurate and granular detection and measurement of wait times and service times as performance indicators of the cardiac care process, but also (and more importantly), as a business intelligence tool for real-time patient flow management.

Most participants knowledgeable in these technologies also acknowledged informally that this was the first time they saw a working prototype of a system involving at the same time a BPM engine (with mobile iPad interfaces), a CEP engine, an RTLS, a message broker, and an analytics interface.

According to the survey results, 82% of the participants at Osler considered that LA-BPMS would improve patient flows and would be better than what exists today, and more than 50% believes that the technology should ideally be deployed within the next 2 years.

On a more theoretical front, this evaluation also confirmed our hypothesis that many types of wait times actually *require* a BPM combined with a RTLS to be computed (i.e., one or the other on its own is insufficient). Out of the 29 types of complex events computed by the CEP for the cardiac care process:

- 10 (34.5%) are inferred using the BPM information only (e.g., OrderExecutionCompleted and RequestForAdmission);
- 10 (34.5%) are inferred using the RTLS information only (e.g., PhysicianInED and PatientOutCCL);
- 9 (31%) required *both* BPM and RTLS information to be inferred (e.g., ConsultationStarted and PatientTransportCompleted).

This is an important result that confirms the necessity of a system such as LA-BPMS for *accurate* and *timely* computation of wait times in healthcare.

5 Comparison

A brief comparison between existing approaches in the literature (Chapter 2) and our own LA-BPMS approach highlights interesting aspects important to our context.

First, in the work by van Hee et al. [19], the framework of adaptive workflows improves the information flow between healthcare providers and patients. The three theoretical process modeling concepts of adaptivity, adaptability and separation of concerns presented in the framework are really key to achieving a flexible workflow-based information system. However, the presented implementation example of the framework does not necessarily reflect or exploit the power of the framework. The YAWL modeling language, which is used to implement a workflow example, does not have semantics that fit naturally with separation of concerns and adaptability in the way a more suitable language like BPMN does. Also, no concerns about scalability and workflow performance are addressed.

In the approach of Zhang et al. [21], many limitations are recognizable. Compared to our implementation, their workflow-based RIS targets a less time-critical type of workflows. The entire radiology processes usually occur in the course of several weeks or months. They are significantly less complex (from a flexibility point of view) than, for example, cardiac patient processes and, in general, emergency care processes. Moreover, the measurement of wait times is simply based on the difference or gap between two given activities. This approach has been argued to potentially be inaccurate (yet still sufficient for their domain scenario) as it does not guarantee the measurement is representative of the actual *patient* wait time we are trying to measure.

Finally, in Poulymenopoulou et al.'s cloud-based workflow system for EMS [10], a strong and unique emphasis is put on implementing an efficiency system while still enabling interoperability between entities involved in EMS using known standards such as Integrating Healthcare Enterprise and OASIS' Emergency Data Exchange Language (EDXL). Security concerns are also taken into consideration using open authentication protocols. However, similarly to van Hee et al., wait time monitoring and more generally, patient flow performance, is not addressed.

These other approaches do not concretely address the issues of improving data integration and visibility using a process automation approach. Moreover, these approaches seldom deal with the ability to *accurately* measure wait times, in a *timely* way. This is caused in part by their inability to track *locations* in real-time, and their limited ability to monitor *patient states* as they occur. Even computing service times (which is a simpler problem than wait times) is problematic in the approaches of van Hee et al. [19] and of Poulymenopoulou et al. [10].

6 Conclusion

This paper has shown how leveraging the context information of a process can be used to enhance and to retrieve better, more accurate, and more timely information about process real-time state. This acute visibility of one's care process operations can be a substantial differentiator for flow managers to efficiently make informed decisions in their daily management of patient flow issues. This flux/stream of data can always help in long-term flow management while facilitating physicians and nurse life in coordinating together, and in delivering the right care to the right patient at the right time.

In conclusion, we have presented how a location-aware business process management system can be used to monitor the operational state of a cardiac care process in real-time. More precisely, we have contributed:

- An abstract LA-BPMS architecture for monitoring a cardiac care process in real-time, including accurately measuring wait times and service times (Section 3.5).
- A smart integration of location awareness capabilities to BPMS using RTLS and CEP technologies (Sections 3.3 and 3.4).
- The concrete development of a prototype tailored for a specific example of a real process of an Ontario hospital and involving the instrumentation of a cardiac clinical pathway to shape the care process models (Section 4).
- Results from the demonstrations and thorough evaluations organized in over 20 sessions with stakeholders sharing various point of consideration and views on the system performance (Section 4).

Several future work items have been identified:

- A formal usability study is required to further validate (from a usability and efficiency viewpoint) the various mechanisms composing LA-BPMS from the point of view of the users.
- A system implementation that tackles a more complete and complex cardiac care process (especially involving exceptions) should be designed and demonstrated.
- Tolerance to false-negatives in the observation of complex events needs to be studied.
- The system also needs to be applied to other clinical pathways, in different hospitals, for generalization.
- HIS connectors should be implemented and tested (e.g., Meditech test system).
- An integration with a real-time simulation engine for supporting near-future, operational decision making [2] is under development.
- Security and privacy concerns need to be addressed since this is a major compliance point for healthcare information systems.

As a final thought, we believe that the specific combination of the presented technologies (BPM, RTLS and CEP) truly has the potential to provide better visibility and high-quality data in real-time to benefit various scenarios of specific problematic areas of healthcare, primarily related to the issue of wait time management.

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