Eindhoven University of Technology

MASTER

A performance measurement framework for clinical pathways monitoring

Meenakshy, P.

*Award date:*
2013

# A Performance Measurement Framework
for
Clinical Pathways Monitoring

in partial fulfillment of the requirements for the degree of
*Master of Science in Business Information Systems*

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# *Preface*

This report is the outcome of the graduation project for completing my Master of Science degree in Business Information Systems program at Eindhoven University of Technology. The research was carried out at the department of Industrial Engineering & Innovation Sciences in co-operation with Catherina hospital, Eindhoven.

I am taking this opportunity to thank a few people who have contributed to this research in their own way. I would like to thank my supervisor Uzay Kaymak for the research topic and guidance. I would also like to thank my colleagues for their ideas and conversations during the research. Thanks go to my family and friends who always had time to listen and gave me inspiration.

I am glad I took the opportunity to continue studying in such an interesting field and it is one of the valuable experiences I had so far.


Parvathy Meenakshy

August 2013

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# 1. Introduction

Healthcare domain around the world is facing challenges due to the skyrocketing cost, chronic illness, ever increasing ageing population, sedentary life style and changing demographics. There is an intense pressure to balance cost and quality of care. Several researches are conducted to investigate the benefits of adopting process orientation and process oriented information systems in healthcare (Lenz & Reichert, 2007) which ascertain the fact that process orientation can improve the quality of care, efficiency and cost effectiveness (Fryk & Steins, 2010). Clinical pathway is an example of process management tool in healthcare to streamline process and standardize care.

Clinical pathway is one of the structured care methodologies which has shown to reduce cost, improve process efficiency and patient outcomes (Williams, et al., 1998). "*A clinical pathway is a multidisciplinary outline of anticipated care, placed in an appropriate timeframe, to help a patient with a specific condition or set of symptoms move progressively through a clinical experience to positive outcomes*" (Middleton, Barnett, & Reeves, 2001). It specifies a series of clinical interventions, timeframes and expected outcomes in the care process of a specific disease for a homogenous patient group based on evidence and clinical knowledge adapted to a specific organizational setting.

The concept of clinical pathway has evolved from the production process in manufacturing industry, wherein the variation in process and timing is monitored to track changes and make improvements (Every, Hochman, Becker, Kopecky, & Cannon, 2000). In healthcare domain, it is used as visual representation of patient's journey showing the clinical outcomes and state transitions along a timeline. Since 1980 clinical pathways have been used in healthcare domain. The early clinical pathway management was based on paper. The electronic version of paper based pathway has been developed in the early 1990s based on a linear sequential model. The state transition model was later designed to improve the capability of a pathway in the late 1990s (Wakamiya & Yamauchi, 2009).

The main components of a clinical pathway are intervention, outcome, temporal aspects, variance and resources (Ye, Jiang, Diao, Yang, & Du, 2009). Intervention consists of different categories of clinical activities/task and outcomes are the results of these interventions. The temporal aspects cover the time line of these interventions and outcomes. Any deviations from the pathway that occur during the patient care process are known as the variances. Resources represent the multi-disciplinary team which comprises of clinicians (physician, nurses) in the different departments of the healthcare organization.

## 1.1 Thesis context and motivation

The development of clinical pathway follows the Plan-Do-Check-Act (PDCA) model of Continuous Quality Improvement (CQI) (Wakamiya & Yamauchi, 2009). The plan and do phase constitute the development and implementation of the pathway. The check phase compares the outcome against predefined clinical pathway and analyses the differences to identify potential improvement. The act step applies the identified improvement to next PDCA cycle.

Literature reveals that implementing a clinical pathway itself will not be sufficient to streamline the care process. In practice, pathway evaluation is carried out to analyze the effect of pathway implementation in the hospital. This is done by comparing the impact of pre and post implementation (Panella, Marchisio, & Di Stanislao, 2003). This is more like an effect comparison, rather than a continuous follow up. In order to ensure a continuous quality and efficiency improvement in pathway, this analysis should be executed in a continuous loop.

The actual execution and continuous monitoring of the pathway is of utmost importance for improvement. The monitoring of the pathway is essentially the measurement of indicators and its reporting to analyze the performance of the pathway. The problem lies in the measurement and analysis of these indicators primarily due to the lack of a performance measurement system. Manual measurement and analysis of indicators are difficult, time consuming and are susceptible to errors, because of the ambiguity of natural language.

## 1.2 Research goal

Error rate can be minimized by defining the indicator and its data elements unambiguously (Anema, et al., 2013). In other words the data elements need to have an explicit specification. Moreover the automatic measurement of these indicators saves time and provides reliable results. Towards this, a formal representation of the data elements of the indicator and an automatic measurement system has to be developed.

For quantitatively analyzing the performance of the pathway, the formal representation of indicators and a framework for automatically measuring these indicators are essential.

Therefore, the main goal guiding this research is:

*Develop a framework for performance measurement system for clinical pathway monitoring.*

Th*e sub goals to be achieved are:*
- *Develop clinical pathway indicator ontology*
- *Develop a formal method to define indicators*
- *Develop a  performance measurement system*
- *Implement a Proof of Concept of the proposed system*
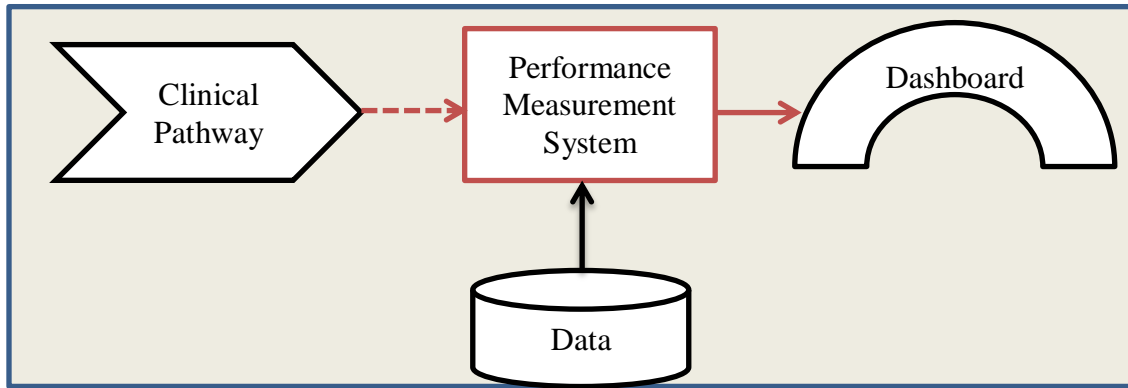


**Figure 1: Context of the research**

The scope and context of the research is shown in Figure 1, where the system will measure the indicators of clinical pathway using the data from electronic patient record and provide the user with an interface to run, view and define indicators.

## 1.3 Thesis Contributions

In order to increase the degree of automation in measuring pathway specific indicators, representation of indicators in natural language is an issue. Even though the formal representation is a solution to this problem, the extent to which machines can intelligently perform the desired tasks is still limited. An alternative for this is to add semantics to the formal representation, and thus make the information understandable for the machines which will enable automatic information processing and exchange.

The World Wide Web Consortium (W3C) has proposed a series of technologies that helps in building semantic based representation and processing of web information (W3C Standards Semantic Web, 2013). These Semantic Technologies are used in this thesis research to solve the problem of automating the measurement of indicators.

## 1.4 Research Methodology

To satisfy the research goal and to solve the problem statement, a methodology is followed throughout the research as shown in Figure 2. It starts with a *literature study* to investigate in general about clinical pathways and analysis of clinical pathways. Furthermore topics such as pathway implementation, monitoring, indicators of pathway are analyzed to understand the state of art in clinical pathways monitoring. In order to use the semantic technologies approach in implementing the performance measurement system, a considerable amount of research has been done to understand the standards and technologies needed to implement such a framework.

The next phase is the conceptual *design* of performance measurement system based on the literature study and the goal of a reusable framework for measuring the indicators of any pathway. A thorough research of the tools and technologies are also conducted in this phase to start the *implementation* phase of the system. The research is finished with the *validation and verification* of the system and identification of open issues.
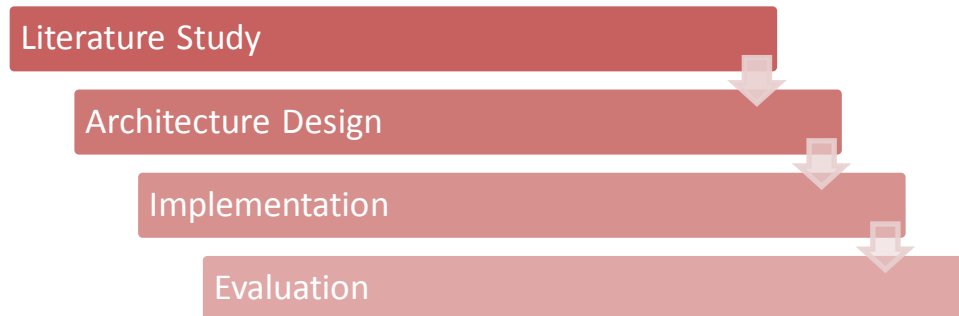


Figure 2: Research Methodology

## 1.5 Thesis Outline

In the next chapter, findings from the literature study about clinical pathways, monitoring and about pathway specific indicators are discussed. Chapter three has the details about semantic web and semantic web technologies that are widely used in building a semantic application.

The fourth chapter is dedicated to the architecture of the proposed system. The components in the architecture and the approach used to design the components are discussed in detail in this chapter.

The proof of concept implementation is presented in chapter five. Furthermore, the implementation details of the web application are explained in this chapter.

The sixth chapter discusses the findings of the research in semantic technologies and the performance measurement framework.

Finally, in the last chapter a summary, the limitations of the project, future work aiming at solving existing problems and improving the results of the project are discussed.

# 2.   Clinical Pathways

## 2.1 Healthcare challenges and process orientation

Healthcare organizations are under increased pressure to improve the quality of care, efficiency, patient safety and cost effectiveness (Saltman & Figueras, 1997).   Adoption of process management approaches in industries has proven that process quality improvement strategies are more effective than product oriented programs (Chae, Kim, Tark, Park, & Ho, 2003). A process is defined as a "specific ordering of work activities across time and place with a beginning, an end, and clearly identified inputs and outputs: a structure for action" (Davenport, 1993). The focus on business processes implies a strong emphasis on how work is done within an organization, in contrast to a focus on what is done. Process oriented design focusses on cross functional processes rather than functional departments.

Therefore process management approaches have been introduced in healthcare domain to improve the quality of care and make it more cost efficient. Clinical pathways and guidelines are attempts to standardize medical practice and thus reduce the fragmentation of practicing medicine (Welland, 1997).

Clinical pathways concept was first introduced by Karen Zander and Kathleen Bower at the New England Medical Center in Boston (Massachusetts, USA) in 1985. They are adapted from Standard Operating Procedures (SOP) which is used in industries to achieve process improvement (van Dam, et al., 2013). SOP is defined as "detailed, written instructions to achieve uniformity of the performance of a specific function"

Nowadays clinical pathways are widely accepted as a process management tool in healthcare which helps in cost effective patient management while maintaining a high standard for quality of care. Pathways are usually developed for high-volume, high-cost disease entities, for low-risk patients in a hospital setting. One factor which helps in cost saving is the short delay time because of the standardization of the activities (Mauro, Happle, Sunyaev, & Krcmar, 2010).  This standardization further reduces variation and thus helps in reducing the probability of medical errors (John, Corrigan, & Donaldson, 2000).

## 2.2 Guidelines and Pathways

The Institute of Medicine defines clinical guidelines as the "systematically developed statements to assist practitioner and patient decisions about appropriate health care for

specific clinical circumstances". Guidelines are treatment guides or algorithms developed by experts in a specialized field of medicine.

Pathways describe a timeline protocol of disease process that involves personnel and services for patient care. Personnel include the primary care physician, specialist, nurses, laboratory, radiology, and the facilities to which the patient is transferred in the period of care. Clinical pathways are evidence based, developed for a specific diagnosis or procedure by multi-disciplinary teams managing the care process. They help in having an explicit model of care and improve multi-disciplinary communication and team work. The multidisciplinary team developing the pathway is composed of different types of physicians, nurses, social workers and administrators, who manage disease processes and are responsible for patient care. Unlike clinical guidelines, pathways are defined for a concrete setting and include a sequence and time frame of interventions (Lenz & Reichert, 2007).

Variance is a key feature of the pathway which is defined as "any event that occurs and is not specified in the clinical pathway or any event, which does not occur within the correct timeframe and is specified in the clinical pathway". These variances occur due to many reasons like patient's condition or complication, refusal to treatment, clinical decisions or delays. Analysis of these variances and identification of factors which can contribute to improvement of variances are key factors in process improvement (Every, Hochman, Becker, Kopecky, & Cannon, 2000).

## 2.3 Definition of clinical pathway and goals

The European Pathway Association (EPA) uses the terms 'clinical pathway' and 'care pathway' as synonyms. According to EPA "*care pathway is a complex intervention for the mutual decision making and organization of care processes for a well-defined group of patients during a well-defined period.*" They state the key characteristics of care pathway as follows:

*"(i) An explicit statement of the goals and key elements of care based on evidence, best practice, and patients' expectations and their characteristics;*
*(ii) the facilitation of the communication among the team members and with patients and families;*
*(iii) the coordination of the care process by coordinating the roles and sequencing the activities of the multidisciplinary care team, patients and their relatives;*
*(iv) the documentation, monitoring, and evaluation of variances and outcomes; and*
*(v) the identification of the appropriate resources.* "

The key focus of the pathway is to enhance the quality of care by improving outcome, optimized resource usage, patient safety and satisfaction. De Bleser et al (2006) conducted a survey for identifying the definitions and characteristics of clinical pathway in literature from 2000-2003. Based on that survey, they identified about 12 categories of aims and outcomes of clinical pathway: efficiency of care, evaluation, quality of care, decreasing variances, clinical outcomes, change of processes, improving compliance, effects on patient satisfaction, improving data collection, improving best practices, and accountability.

In general, the aim of a clinical pathway is to improve the quality of care, reduce risks, increase patient satisfaction and increase the efficiency in the use of resources (De Bleser, 2006).



Figure 3: Goals of pathway

## 2.4 Clinical Pathway Development

Continuous Quality Improvement (CQI) is a quality management approach designed by Dr. Deming for process improvement. His Plan-Do-Check-Act (PDCA) cycle is used as a tool for implementing improvement in organizations. Clinical pathway management follows the CQI approach (Brayman & Wallace, 2001). The plan phase consist of modeling, the do phase is the execution, measurement of indicators is in the check phase and act phase constitute the analysis. The analysis results provide crucial information for optimizing the pathway and the cycle continues.

Pathway development based on Deming cycle is further improved and developed into a 7 phase method for development, implementation and evaluation of clinical pathways. This 7-phase method consists of a screening phase, a project management phase, a diagnostic and objectification phase, a development phase, an implementation phase, an evaluation phase and a continuous follow-up phase (Vanhaecht, et al., 2012). This method provides an approach to develop a new pathway or improve existing pathway.

Screening phase checks whether the pathway is the right method to improve the care process by analyzing information of the existing care process. Project management phase defines the patient group for which the pathway is developed. It also includes setting up of a project plan and definition of start and end point of care pathway. As-Is situation of the current process is evaluated based on perspectives like organization, patient, evidence and external partners. The sequence and timing of the process is analyzed by interviews and using guidelines and clinical algorithms. In the development phase care pathway is developed based on the information from the previous phases. The inclusion and exclusion criteria of the patient group, key interventions and practical organization of the care process are defined. An implementation plan is



**Figure 4: Seven phases of pathway development (Vanhaecht, et al., 2012)**

made, followed by the actual implementation and pilot testing of pathway is conducted in the implementation phase. The evaluation phase evaluates the usability of the care pathway by effect measurement, measurement of adherence to the pathway and redesigning the pathway if necessary. The last phase is the continuous follow up which keeps the pathway alive. This is ensured by measuring the indicators, analyzing variances, establishing ownership, objective measurement at least once a year and discussions in the core team. The continuous follow up of indicators is essentially monitoring of the pathway.

## 2.5 Clinical Pathway Evaluation & Monitoring

Evaluation and monitoring is often confused and used interchangeably. Evaluation is defined as the "judgment of interventions according to their results, impacts and needs they aim to satisfy" (OECD, 2002). It is used to assess the success or failure of a particular activity. Monitoring is defined as the "continuous process of collecting and analyzing data to compare how well a project, program, or policy is being implemented against expected results." The principal activity of performance monitoring is the

collection of data to facilitate the reporting of performance indicators for the identification of changes produced by an intervention. (Turabi, Hallsworth, Ling, & Grant, 2011). Therefore a system to measure performance indicators is most essential for pathway monitoring and hence improvement.

Researches have shown that there is a lack of continuous follow up after pathways are implemented due to the lack of IT support (Gerven, Vanhaect, Deneckere, Vleugels, & Sermeus, 2010). Manual measurement of these indicators is time consuming and labor intensive. Hence an automated tool for measurement of indicators is a bare necessity for fulfilling the goals of a clinical pathway.

## 2.6 Performance Indicators for Clinical Pathway

The Leuven Clinical Pathway Compass is an operational tool designed for pathway evaluation and monitoring (Vanhaect & Walter, 2003). Five domains are identified for defining the indicators of clinical pathways. They are  the 'clinical', 'process', 'financial' 'service' and 'team' domains.



**Figure 5: Leuven Clinical Pathway Compass (Vanhaect & Walter, 2003)**

The *clinical* domain includes indicators related to the disease and their impact. These indicators are specific to a pathway or patient group and measure the progress of pathway to the quality of care. For example the percentage of patients with stroke who are prescribed antithrombotic at discharge is a clinical indicator of stroke pathway.

The *process domain* consist of indicators like waiting time, lead time, the sequencing of interventions and the time between two interventions. These indicators are aligned with the efficiency goal of clinical pathway. The proportion of patients with length of stay greater than 2 hours in emergency room is an example of process indicator of clinical pathway.

The *financial* indicators constitute the cost indicators of pathway. It is vital especially for the hospital management to control the cost of care and at the same time maintain the quality of care. The cost of care is calculated from the number of test conducted, medication, X-rays etc. One method to calculate the financial indicators is the use of Bill--of-Services (BOS) for each pathway (Vanhaect & Walter, 2003). BOS consist of procedures, medications, resources of a pathway. Length of stay of the patient in the hospital is also used as a financial indicator of the pathway.

The service delivery to the patient is covered in the *service* domain. For example patient satisfaction is an indicator in the service domain which measures the patient perception on the quality of care. These are usually measured from questionnaire about the quality of care, the information given by the healthcare professionals etc.

Clinical pathways are used by a multidisciplinary team for improving the communication and team work of care process. The *team* domain includes indicators to measure the effectiveness in sharing goals among this multi-disciplinary team. Clear role definitions, coordination and job satisfaction are used as team indicators of clinical pathways.

## *2.7 Clinical Indicators*

The Joint Commission, formerly the Joint Commission on Accreditation of Healthcare Organizations (JCAHO) defines a clinical indicator as a "quantitative measure that can be used as a guide to monitor and evaluate the quality of important patient care and support service activities". Hence monitoring of healthcare quality is impossible without the use of clinical indicator. Indicators are usually selected on basis of expert judgment and existing scientific evidence (Anema, et al., 2013). Clinical indicators are classified in different ways for different purposes: for evaluating quality of care, for monitoring events, to measure aspects of care like generic or disease specific (Mainz, 2003). They are also classified based on the type of care, function and modality (Schuster, et al., 1997)
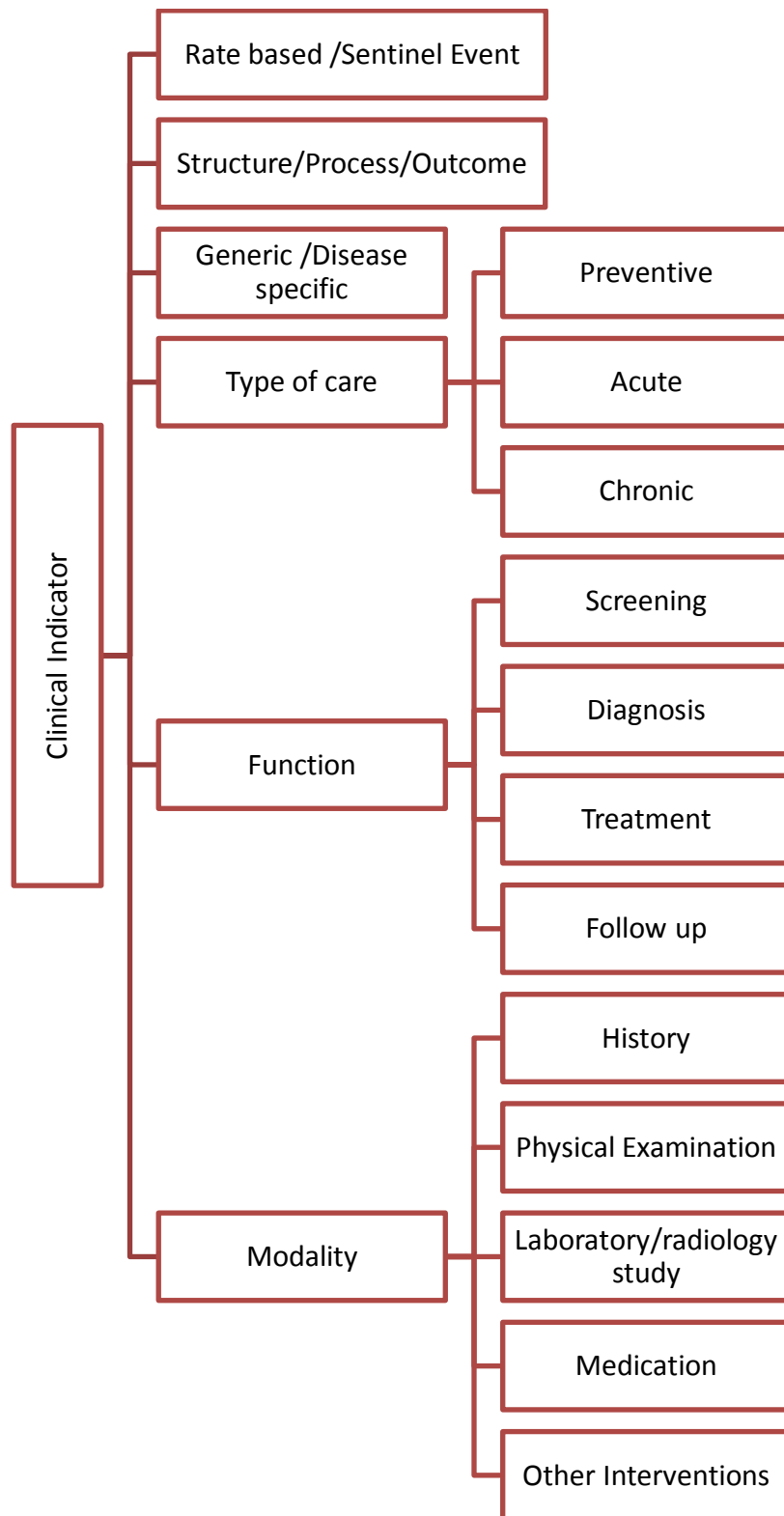
**Figure 6: Classification of clinical indicators**

Clinical indicators are classified into structure, process or outcome to evaluate the quality of patient care (Donabedian, 1988). Structure consists of the attributes of settings in which care is provided. This can be material resources, human resources or organizational structure. These indicators can provide a review of hospital's administration, advanced medical facilities, rationale behind the allocation of resources and the effectiveness of the rules and regulations.



Figure 7: Donabedian framework to evaluate quality of care

Process denotes the activities involved in giving and receiving care. It consists of activities in diagnosis, treatment or interaction with the patient. It is considered as the most common type of indicator since it directly point to the areas which need improvement. They are directly under the control of the physician.

Process of care indicators can be further divided into pharmacologic and non-pharmacologic indicators. Pharmacologic includes prescription for medications, for example, Aspirin prescribed within 3 hours of hospital arrival. Non-pharmacologic indicator denotes waiting time for procedure, measures whether a particular procedure is performed or not. ECG within 10 minutes of hospital arrival is a non-pharmacologic process of care indicator.

Outcome refers to the effects of care delivered. For example, in hospital mortality, readmission, emergency visits are indicators related to outcome.
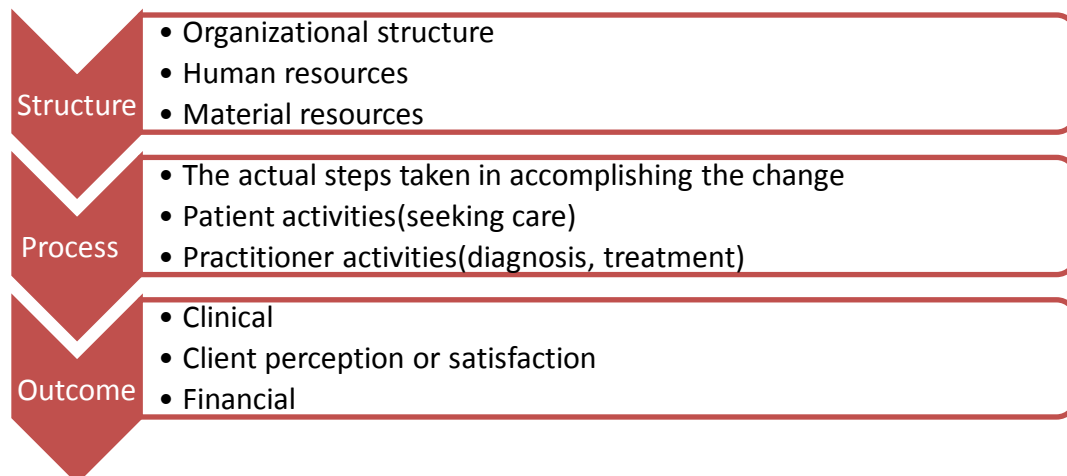


Figure 8: Structure, Process, Outcome indicators

Indicators are classified based on the events as sentinel event or rate based (Decker, 1991). Sentinel indicator measures the unexpected occurrence of a serious event resulting in death or serious injury or risk which is not desired in the natural course of treatment process. It needs immediate investigation and response. Number of patients who die during a surgery is an example of a sentinel indicator.

Rate based indicator is expressed as a ratio which measure the proportion of activities that conform to a desired standard or number of patients with certain outcomes. The numerator of the indicator represents the number of patients who incur an 'event of interest and the denominator represents the number of patients at risk of an event (Howley & Gibberd, 2003). For example, percentage of patients who acquired infection during hospital stay from January 2013 to March 2013 is a rate indicator with numerator as the number of patients who acquired infection and denominator as the number of patients in hospital during the period of January to March 2013.

A clinical indicator consists of: 1) data elements-the specific information needed to measure the indicator, 2) operational definitions- definition of the indicator that allows for reliable measurement across practice settings, 3) Inclusion / Exclusion criteria-specific exclusion and inclusion criteria of the patient group have to be defined, 4) formula for calculating the definition.

Formalization of the indicators and standardization of the data elements are necessary for reliable and unambiguous measurements of indicators (Anema, et al., 2013). Indicators represented in natural language leads to different interpretations and hence error in the indicator scores. Therefore the indicators should be represented in an unambiguous, sharable, machine-processable, standard representation to compute it automatically (Dentler, Teije, Cornet, & Keizer, 2012).

## 2.8 Formal Representation of Performance Indicators

Dentler et al proposed a method for the formalization of indicators represented in natural language. Indicators are represented as semantic queries that retrieve patients who fulfill constraints and are calculated automatically by running against patient data (Dentler, Teije, Cornet, & Keizer, 2012). A query is an expression that specifies properties of the data to be retrieved. Semantic queries are used to retrieve the data in Semantic Web. Their approach of semantic queries is reused in the representation of indicators in this research. The next chapter introduces the concepts of Semantic Web, Semantic Web technologies and semantic queries in detail.

# 3. Semantic Web Technologies

## *3.1 Semantic Web*

The term Semantic Web or "Web 3.0" is a term coined by Tim Berners- Lee as an extension to the World Wide Web (WWW) of today (Berners-Lee, Hendler, & Lassila, 2001). It is a major research initiative of World Wide Web Consortium (W3C) to make the content in the web as a web of linked data equally readable and understandable for humans and machines. Such a web of data will enable web applications to access various sources of data and provide intelligent service. For example, application can then pull data from the upcoming appointments in my Google Calendar and the weather information website page to show weather information in my calendar page. This needs the information to be represented in a common format.

The idea is to complement the natural language text in the web with an explicit semantics based on formal knowledge representation. This can be accessed automatically by machines to interpret the meaning of the information represented in natural language. Resource Description Framework (RDF) is used as the formal language for representing this data. Semantic Web Technologies consists of technologies that help in building semantic based representation and processing of web information.
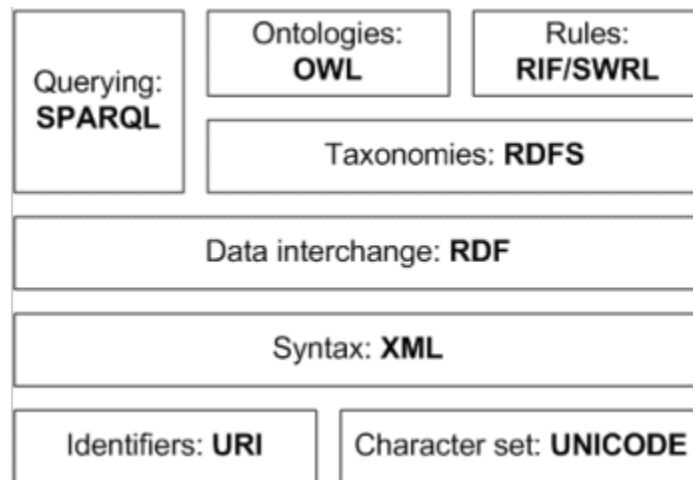


**Figure 9: Semantic Web Technologies**

## 3.2 Semantic Web Technologies

### URI and UNICODE
Uniform Resource Identifier (URI) is used to uniquely identify resources in the web. UNICODE is a character-encoding standard that supports international characters.

### XML
eXtensible Markup Language (XML) is a markup language, composed of a set of rules for encoding documents in machine-readable form, and it is currently considered the standard format for structuring documents. XML allows users to add arbitrary structure to the documents without any meaning about the structure.

### RDF
RDF provides a common framework for representing information in the semantic web. It provides meaning by encoding data in a set of triples. Triples are in the form subject-predicate-object. Subject and Predicate must be URI and Object can be either a URI or a literal. A collection of triples form the RDF graph. The assertion in RDF triple states some relationship indicated by *predicate* exists between the *subject* and *object* of the triple. The meaning of an RDF graph is the conjunction of the statements corresponding to all the triples it contains (Klyne, Caroll, & McBride, 2004).
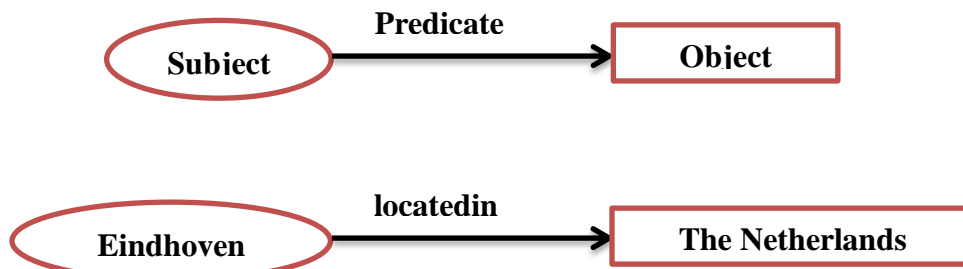
Figure 10: RDF Triple

### RDFS
RDF Schema (RDFS) is an extension of RDF which provides a way to define application specific classes and properties. It also allows specific resources to be described as instances of more general classes.

### SPARQL
SPARQL (**S**imple **P**rotocol **a**nd **R**DF **Q**uery **L**anguage) is the standard query language for RDF data developed by W3C SPARQL Working Group (Prud hommeaux & Seaborne, 2008). It has syntax similar to SQL and it queries RDF graph by pattern

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matching. It consists of a series of clauses which define the desired information, run against a data source specified by URI which returns the result set.

A SPARQL query comprises, in order:

- Prefix declarations, for abbreviating URIs ( PREFIX)
- Dataset definition, stating what RDF graph(s) are being queried (FROM)
- A result clause, identifying what information to return from the query(SELECT)
- The query pattern, specifying what to query for in the underlying dataset(WHERE)
- Query modifiers, slicing, ordering, and otherwise rearranging query results(FILTER, ORDER BY)

The key features of SPARQL are

- pulling values from structured and unstructured data
- exploring data by querying unknown relationships
- performing complex joins of disparate sources in a simple query
- transforming RDF data from one vocabulary to another by combining separate software applications
- updating RDF data in bulk (Feigenbaum & Prud'hommeaux, 2013)

There are four different SPARQL query types

- SELECT query returns tuples matching specified pattern
- ASK query tests for existence
- CONSTRUCT query returns a graph
- DESCRIBE query returns a graph determined by the query engine.

Example of a simple SELECT Query in SPARQL.

Select the country whose capital is Amsterdam

```
PREFIX globe: <http://example.org/globe/>
SELECT ?country
WHERE{
?country globe: hasCapital ?city.
?city globe:hasName "Amsterdam"}
```

## 3.3 Ontology

In computer science, "Ontology is a formal explicit specification of a shared conceptualization" (Gruber, 1993). 'Formal' refers to the fact that it should be machine-readable. In other words it should be in a formal language and hence no ambiguity. 'Explicit' means that the type of concepts used and constraints on their use are explicitly defined. 'Shared' refers to the fact that the knowledge represented are agreed upon and accepted by a group. 'Conceptualization' consists of the identified concepts and the relationships that are assumed to exist and relevant (Studer, Benjamins, & Fensel, 1998).

Ambiguity in the meaning of concepts for humans and computers can be considered as one of the motivation behind ontologies. The problem of using different terminologies to refer to the same concept or using the same term to refer to different concepts leads to ambiguity. Hence there is a need of semantic rich and machine understandable representation of concepts.

Ontology facilitates the communication between people and systems without ambiguity because of the explicit specification. It can be shared and reused for building other ontologies. Ontology is used for communication, computational inference and for reuse and organization of knowledge (Gruninger & Lee, 2002).Artificial Intelligence, Semantic Web, Systems Engineering, Biomedical Informatics, and Information Retrieval are some of the application areas where ontologies are widely used.

### 3.3.1 Types of ontology

Ontologies are classified according to the degree of dependence on a particular task or point of view (Guarino, 1998).

- **Top level ontologies** describe very general concepts and independent of particular problem or domain. Examples of general concepts are space, time, matter, object, event etc.
- **Doman ontologies** and describe the vocabulary related to a generic domain or a generic task or activity. Generic domain can be medicine, automobiles

- **Task ontologies** describe generic tasks or activities. For example 'diagnosis'.

- **Application ontologies** describe concepts of a particular task and particular domain and hence they are related to problem solving methods.

### 3.3.2 Purpose of Ontology

In practice, ontologies are used in a variety of purposes.

| Purpose | Description |
|---|---|
| **Data integration** | Integration of heterogeneous data sources (Wache, et al., 2001) |
| **Data mapping vocabulary** | Mapping to/from existing data sources |
| **Data tagging** | Used in the representation of tagging data: Tag ontologies (Kim , Passant, Breslin, Scerri, & Decker, 2008) |
| **Knowledge Representation** | Data standardization and conceptualization by a formal machine-understandable ontology language. |

**Table 1: Different purposes of ontology**

## 3.4 Languages for ontologies

### Description Logic

Description Logics (DLs) are the corner stone of semantic web. The semantic web ontology languages (OWL) are based on DL. DL is a family of knowledge representation languages used in ontological modeling. DLs are logics and consist of formal semantics: precise specification of the meaning of the ontologies. This formal semantics enables humans and computer systems to exchange ontologies without ambiguity in meaning. Moreover it helps to infer or deduce additional information from the facts stored in the ontology. This is a key feature of the ontology compared to other modeling language like Unified Modeling Language (UML).

DL ontology is conceptually divided into ABox (the assertions box; the data instances box) and TBox (the terminologies box; the data schemas box). The classes and properties of the ontology belong to the TBox and the individuals belong to the ABox.

Ontology language is a formal language used to represent ontologies. The requirements of an ontology language are: 1) a well-defined syntax, 2) a well-defined semantics, 3) efficient reasoning support, 4) sufficient expressive power, 5) convenience of expression (Antoniou & Harmelen, 2004).

The well-defined syntax is for the machine processing of information similar to programming languages. Formal semantics describe the meaning of knowledge and it is required to reason about the knowledge. For eg: If 'Paul' is an instance of class Person and Person is a subclass of Human, then it can be inferred that Paul is an instance of Human class. Automated reasoning is possible only because of the formal representation of the ontology. Reasoning checks the consistency of the ontology and the knowledge, unintended relationships between classes, and automatically classifies instances in classes. Sufficient expressive power is necessary to model the domain of interest.

*Web Ontology Language (OWL)*

OWL is an ontology language standard for web applications of ontologies recommended by W3C. It is introduced for applications to process the content of information than presenting information to humans. OWL has more features for expressing meaning and semantics than XML, RDF, and RDF-S, and thus expressive power of OWL is higher than these languages to represent machine interpretable content. XML provides syntax for structured documents, while RDF(S), followed by OWL provides semantics in terms of Description- Logics.

The OWL class represents the set containing individuals. OWL property represents the binary relations between two classes. The object property represents the relationships between individuals of two classes. It corresponds to the relationships in UML. The data property relates the individual of a class to a data type, similar to the attributes in UML. Individuals represent the objects within the ontology or the members within the class.

| Classes | Properties | | Individuals |
|---------|------------|------------|-------------|
|         | Object Property | Data Property | |
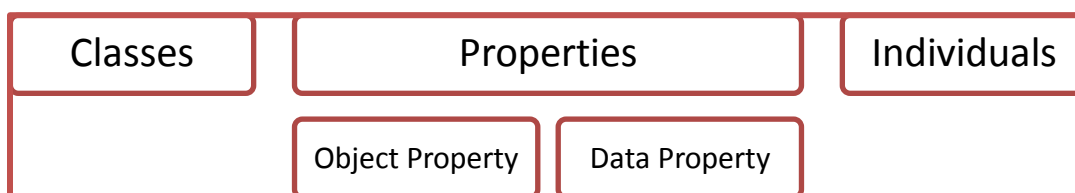
Figure 11: Components of OWL

The OWL Ontology follows an Open World Assumption (OWA). The Open World Assumption has three important characteristics. 1) The information contained within the ontology is incomplete 2) It is assumed there can always be more information 3) Something does not hold unless it is explicitly stated.

## *3.5 Ontology Engineering*

Ontology engineering is a set of tasks related to the development of ontologies for a particular domain. It is defined as the " the set of activities that concern the ontology development process, the ontology life cycle, the methods and methodologies for building ontologies, and the tool suites and languages that support them" (Gómez Pérez, Fernández-López, & Corcho, 2004). There are a lot of methodologies which address the development and maintenance of ontologies. Following is a description of the most popular ontology development methodologies in the literature.

Uschold and King (1995) developed a methodology for building ontologies from scratch and according to their method the development should be guided by motivating scenarios. They proposed four phases in the ontology development: 1) identify purpose and scope of ontology, 2) build the ontology, 3) evaluate the ontology and 4) document the ontology. They also suggest a top down approach, bottom up approach and middle out approach for identifying the main concepts in the ontology (Uschold & King, 1995).

Toronto Virtual Enterprise Method (TOVE) (1995) consists of four steps: 1) description of motivating scenarios, 2) formulation of informal competency questions, 3) specification of ontology terms using a formal representation, 4) formulation of formal competency questions using a formal language, 5) axiom specification, 6) verification of ontology completeness (Gruinger & Fox, 1995).

Methontology (1997) is an ontology methodology which is based on the IEEE standard for software development. It suggests which activities should be accomplished when building ontology, but does not provide guidance as to how they should be carried out. The activities are 1) plan, 2) specification (scope and goal), 3) conceptualization (elicit the relevant concepts), 4) formalization (using formal language - DL), 5) integration (with existing ontologies), 6) implementation (using formal ontology language), 7) evaluation, 8) documentation and 9) maintenance (Fernandez Lopez, Gomez-Perez, & Juristo, 1997)

Ontology development 101 (2001) is a simple knowledge engineering methodology to develop ontologies. It is based on declarative knowledge representation systems (Noy & Deborah, 2001). It is an iterative approach and the authors developed this based on their experience using ontology editing environment like Protégé. It is one of the most cited methodologies for ontology development using Protégé. The methodology consist of 7 steps 1) determine the domain and scope of the ontology, 2) consider reusing existing ontologies, 3) enumerate the important terms in the ontologies, 4) define the classes and

class hierarchy, 5) define the properties of the classes, 6) define constraints and 7) create instances.

## 3.6 Biomedical Ontologies

Biomedical ontologies represent the knowledge of medicine and biology in a systematic way. Efforts to standardize the vast information in biomedical domain resulted in classification of diseases, controlled vocabularies, thesauri, terminologies or ontologies.

### 3.6.1 SNOMED CT

The Systematized Nomenclature of Medicine, Clinical Terms (SNOMED CT) is a comprehensive clinical and medical ontology that covers a wide range of concepts in the domain, including anatomy, diseases, pharmaceutical products, clinical findings and medical procedures (SNOMED CT, 2013). It is evolved from the Systemized Nomenclature of Pathology (SNOP) developed by the College of American Pathologists (CAP) which is later extended to SNOMED CT. It is now owned by the International Health Terminology Standards Development Organization (IHTSDO), a not-for-profit association in Denmark. It is the most comprehensive clinical terminology used for indexing, storing, retrieving and aggregating clinical data across specialties and sites of care.

It contains about 300,000 active concepts with unique id, meaning and formal logic based definitions. The core structure of SNOMED CT comprises of three components, which are Concepts, Descriptions and Relationships. Each concept has description and one or more semantic relationship to other concepts. The relationships are classified into two categories- IS A (sub-type/super-type) and attribute relationship. It uses the formal semantics of Description Logic (DL) which enable the automated reasoning.

Each concept is represented by a unique numeric identifier (concept Id) and thus it provides a standard by which medical conditions and symptoms can be referred, avoiding the ambiguity of regional terms. Moreover it facilitates the electronic exchange of clinical information among health care providers and electronic patient records (EPR) systems. Due to its appropriate underlying logical formalism and coverage, SNOMED CT is referred as the standard for developing the ontology in this research.

### 3.6.2 LOINC

The Logical Observation Identifiers, Names, and Codes (LOINC) is a universal code system for laboratory tests and clinical observations (LOINC, 2013). There are mainly two types of entities in LOINC- the first type consist of laboratory tests and clinical observations and the second type consists of entities for their description. Unlike SNOMED CT, LOINC does not use any formalism like Description Logic (DL). But it has a template represented in 6 axis and named semantic relationships which enable them for automatic processing.

| Definition axes | Function | Example |
|---|---|---|
| Component name (analytic) | What is measured, evaluated or observed | Creatinine, glucose |
| Property measured | Characteristics of what is measured | Mass concentration |
| Timing | Interval of time over which the observation or measurement was made | Average, moment in time |
| Type of sample | Context or specimen type within which the observation was made | Urine, liver |
| Type of scale | The scale of measure | Quantitative, ordinal, nominal |
| Method (where relevant) | Method or procedure used to produce the result or observation | optional |

**Table 2: Six definition axes of LOINC**

### 3.6.3 ICD 10

International Classification of Diseases (ICD) is developed and maintained by World Health Organization (WHO). It is used to classify disease, related health problems and procedures. The latest version ICD10 has both clinical and procedure codes.

### 3.6.4 UMLS

The Unified Medical language System (UMLS) is a database of medical terminology provided by the US National Library of Medicine (NLM). Terms from different databases like LOINC, SNOMED CT are unified so that different terms are identified as the same medical concept (Unified Medical Language System, 2013). The UMLS identifies equivalent terms across terminologies and groups them into one UMLS concept. The goal is to facilitate an intelligent system for improved access to biomedical information.

| Name | Scope |
|------|-------|
| **SNOMED CT** | Medical terms for clinical documentation & reporting in EPR |
| **LOINC** | Clinical observations & laboratory tests |
| **ICD 10** | Classify disease and health problems |
| **UMLS** | Integrates terminology, classification and coding standards |

**Table 3: Summary of the scope of SNOMED CT, LOINC, ICD10, UMLS**

## *3.7 Ontology Editor Tool: Protégé*

Ontology modeling/editor tools are used to create or manipulate ontologies through a graphical user interface. Protégé is open source ontology editor software developed by Stanford Medical Informatics department of Stanford University. It is one of the most dominant and domain independent tools used for ontology development (Khondoker & Mueller, 2010). There are two main ways of modeling ontologies in Protégé each has its own user interface: Frame based and OWL. The Protégé Frames editor is based on Open Knowledge Base Connectivity (OKBC) protocol enables users to build and populate frame based ontologies. It consists of classes which represent the concepts, slots representing the properties and relationships, instances and facets are restrictions on the slots.

The Protégé OWL editor is used to build ontology for the Semantic Web. It consists of classes, properties and individuals. Protégé ontologies can be exported into a variety of formats including RDF(S), OWL, and XML Schema. There are a large number of third-party plugins that extends the platform's functionality (Rubin, Noy, & Musen, 2007). The Protégé OWL editor comes with a reasoner engine to check consistency of the ontology. A reasoner is a program that infers logical consequences from a set of explicitly asserted facts or axioms and typically provides automated support for reasoning tasks such as classification, debugging and querying.

# 4. Proposed Framework for Performance Measurement System

In the previous chapters, the need of a system for measuring the indicators of pathway is motivated. Furthermore semantic technologies and tools are introduced which is used in the system developed for measuring indicators. This chapter presents the proposed frame work of performance measurement system.

## 4.1 Approach

The clinical pathway is developed based on interviews, medical guidelines and the protocol followed in hospital for a particular disease. Performance monitoring of these pathways are conducted to check the progress of pathway towards the goals. This involves the measurement of indicators related to the various domains of pathway and further analysis of the measurements to take actions for improvements. A literature study is conducted to analyze the existing system which measures the pathway specific indicators and it has been found that continuous follow up of indicators are not performed due to the lack of a system for performance measurement. Hence a system is developed and implemented to enable the measurement of indicators automatically.

The aim of a performance measurement system is to automate the measurement of indicators from the electronic patient data of the hospital. Developing a performance measurement system follows a step by step approach starting from the identification of pathway specific indicators. The indicators specific to pathway are identified from clinical guidelines, pathway evaluation researches and discussions from the hospital professionals. A list of key indicators is prepared and confirmed with the multi-disciplinary team following the care pathway. Furthermore the inclusion, exclusion criterion, the formula for calculating each indicator is defined.

In order to formally conceptualize the data elements in the indicator, an ontology of the indicators is created. This provides an unambiguous semantics to the data elements (concepts) of the indicator. The methodology of ontology development, the decisions made in each step and the actual implementation of the ontology is further explained in Section 4.2 and Section 5.1 respectively.

The indicators represented in natural language have to be translated to formal representation in order to compute it automatically. The formula for computing the indicator is represented using SPARQL query. Based on the ontology, the triple pattern

of the SPARQL query is formulated. The indicators are calculated by executing the query over the patient data recorded in the electronic patient record. In order to query this data in SPARQL, the data has to be translated to an RDF data model. The queries are executed over the RDF data model and the corresponding indicator values are calculated. The following sections will introduce the conceptual architecture and the details of each component of the architecture.

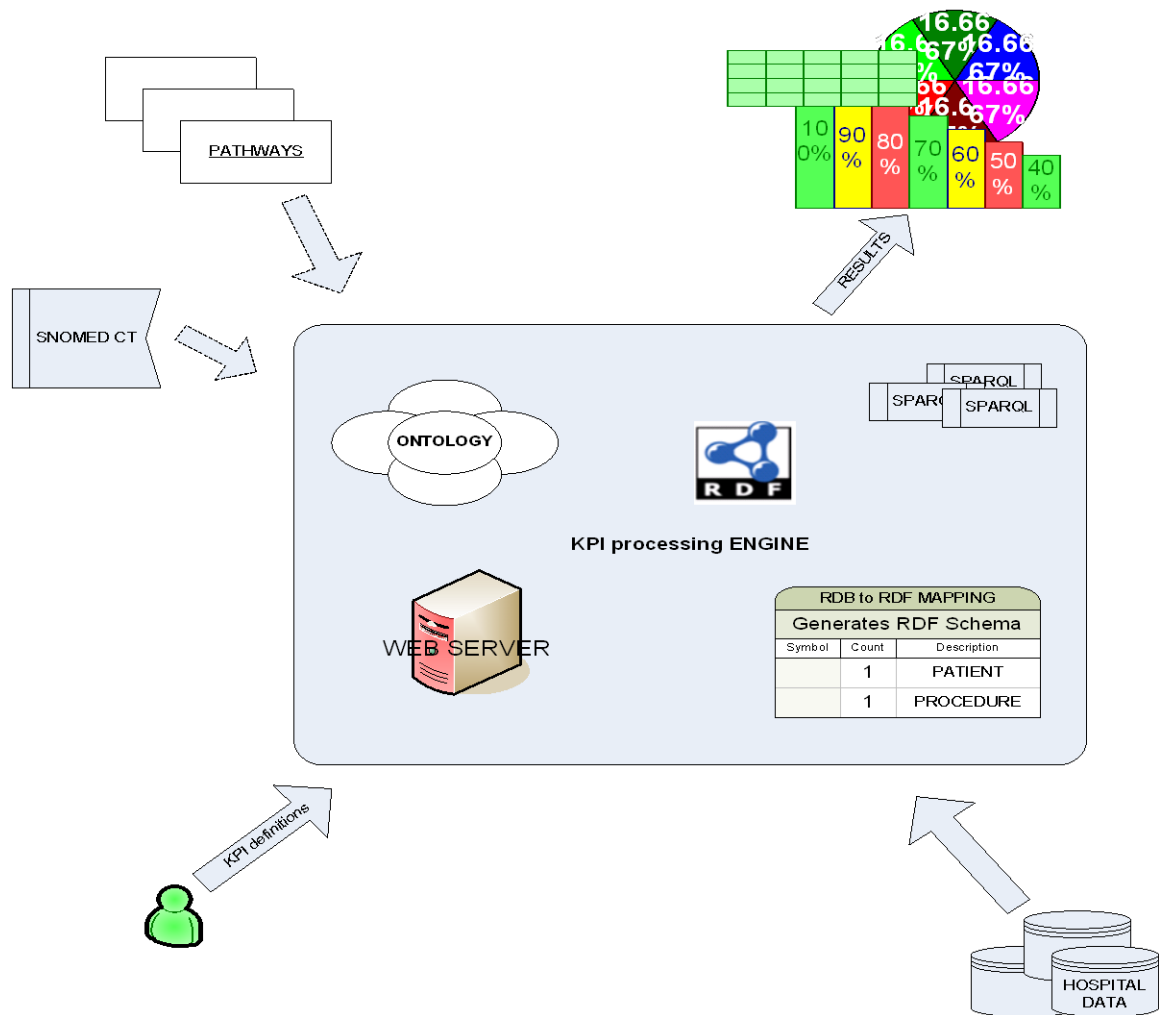## *4.2 Architecture of performance measurement system*



**Figure 12: Conceptual Architecture of performance measurement system**

The conceptual architecture consists of inputs such as clinical pathways, SNOMED CT and indicator definitions which are used to develop the ontology. Hospital data in relational database is shown to represent the data source for measuring the indicators. The output of the system is a user interface developed for running, viewing and scheduling measurement of indicators. The development of each component in the architecture is further explained in the following sections.

## 4.3 Indicator Ontology

The ontology of the indicators of the pathway is the most important component of the framework. This ontology is a type of application ontology, modeled for the purpose of formally specifying the data elements of the clinical indicator.  It closely follows the structure and definitions of SNOMED CT.

This ontology is focused on the basic building block of clinical indicators, which means the basic concepts are covered. But the ontology is not comprehensive, for example, it does not cover all types of disease or drugs. Over time, the ontology can be expanded incrementally for other types of indicator.

 A literature study is conduced to analyze the performance aspect of clinical pathway and the concepts in pathway performance. A review of other clinical pathway ontologies (Zhen, et al., 2009) (Ye, Jiang, Diao, Yang, & Du, 2009) (Dimitrios, Gregoris , Pardalis, & Bouras, 2009) (Hurley & Abidi, 2007) is also conducted to understand the categories used in the pathway ontologies. Later ontology is created in an online mind mapping tool called MindMeister (MindMeister, 2013). The ontology is developed in OWL using Protégé editor.

One of the best practices while developing ontology is to build it incrementally considering the time constraints and the purpose (Bergman, 2010). So in this research, the scope of the ontology is considered smaller with a less coverage of depth achieving the productive use of the ontology.

### 4.3.1 Ontology development

The ontology is developed based on Ontology Development 101 explained in Chapter 3.3. This methodology follows an iterative approach and the modeling decisions are primarily based on the projected task. Evaluation is carried out by using it in the specified application and then revising the initial ontology. The figure shows the major steps in developing the ontology. Each step is further elaborated below.
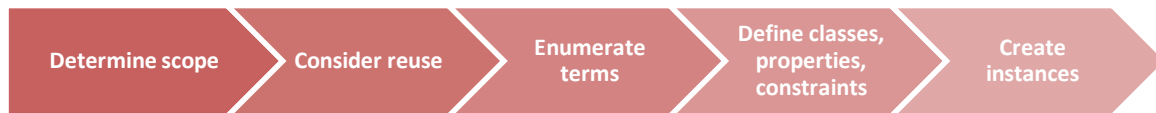
**Step 1: Determine the domain and scope of the ontology**

In this research, ontology provides an explicit specification of data elements used in the clinical indicators of a pathway. The data elements in the definitions of indicators are represented by the classes in the ontology. Hence ontology provides a vocabulary for indicator definition. The domain is clinical pathway indicators and the scope of the ontology is the clinical dimension of pathway indicators. The clinical dimension is considered since it covers the pharmacologic and non-pharmacologic processes of care indicators which are the most important measures for judging quality of pathway (Lilford, Brown, & Nicholl, 2007).

**Step 2: Consider reusing existing ontologies**

Reusing structure and vocabulary of existing ontology is a best practice in ontology development. However none of the existing pathway ontology would be useful to be reused directly since it does not cover the aspects of indicators of pathway. Thus a whole new set of ontology have to be developed for indicators of pathway. The temporal aspect of the indicators can be represented using the OWL time ontology developed by W3C (Time Ontology in OWL, 2013).

**Step 3: Enumerate important terms in the ontology**

The important terms in the ontology are identified from the definition of pathway, the pathway model and the performance indicators of the pathway. According to the definition of pathway by European Pathway Association (EPA), the important concepts are interventions, patients, time period, roles, activities, variances, resource, outcomes etc (European Pathway Association, 2013). Analyzing the characteristics of clinical indicator sets of various pathways led to the identification of concepts like *drug, procedure, time instant, interval, clinical state, history of patient, allergies etc*

**Step 4: Define the classes and the class hierarchy**

The classes are defined using a top down approach by specifying the most general concepts in the top layer followed by the specialization of concepts. The clinical pathway

indicator sets of disease like stroke, chronic renal failure, heart failure given in Appendix B are used as reference while developing the classes of ontology.

One of the best practices of ontology development is to build it incrementally with a small scope and small set of classes. The identified terms are arranged in taxonomic hierarchy of classes and subclasses.

Every pathway is specific to a disease and the clinical indicators measured are for the proportion of patients with a particular disease. Therefore '*Disease'* class is specified as a top level class. Acute disease, chronic disease, infectious disease and allergy are defined as their subclasses. Drug is an important concept in the clinical indicators and so it is added as a top level class. "Concepts in finding hierarchy represent the result of a clinical observation, assessment or judgment, and include both normal and abnormal clinical states" (SNOMED CT User Guide, 2013). Clinical finding has subclass complication. Situation has subclass procedure refusal since this concept commonly appears in the criteria of clinical indicator. Measure is added as a class to specify the aggregate measures used commonly in clinical indicators. Participant class consist of three subclasses: facility covers the device and space used in the procedure.

Organization Unit class consist of departments. Personnel include the subclasses: hospital personnel consisting of the multi-disciplinary team and patient. The procedure class is one of the most important classes in the ontology, since it represents activities performed in the provision of health care. "This hierarchy represents a broad variety of activities, including but not limited to, invasive procedures, administration of medicines, imaging procedures, education procedures and administrative procedures" (SNOMED CT User Guide, 2013). Procedure class has subclasses: administrative procedure, diagnostic procedure, therapeutic procedure, evaluation procedure and laboratory procedure.

The temporal class is added to specify the time related aspects of indicator. It has subclasses: instant and interval.
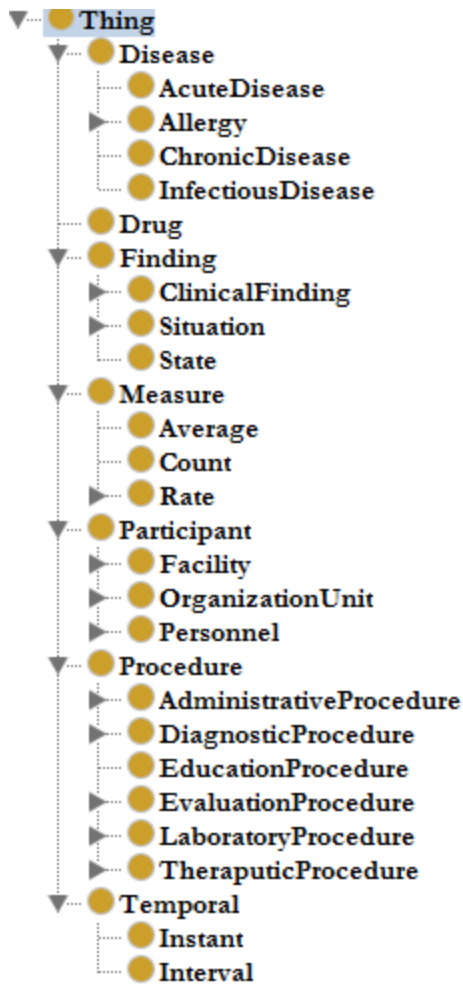
**Figure 14: Clinical indicator classes**

**Step 5: Define the properties of classes**

Properties are binary relations (relations between two things).Properties may have a domain and a range specified. They link individuals from the domain to individuals from the range. The properties of classes are defined using the object properties and data properties. Object properties are used to define the relationship between individuals of classes and data properties are used to define relationship between individual and literals.

Following show the list of properties with the domain and range.

| Object Property | Domain Class | Range Class |
|---|---|---|
| **hasUndergoneProcedure** | Patient | Procedure |
| **hasDisease** | Patient | Disease |
| **hasFinding** | Patient | Finding |
| **hasHistoryOf** | Patient | Disease |
| **hasPrescription** | Discharge | Drug |
| **nonUse** | Situation | Drug |
| Data Property | **Domain Class** | **Range Class** |
| **hasDateTime** | Procedure | Datetime |

**Table 4: Properties in the ontology**

For example, the property 'hasUndergoneProcedure' links the individuals of patient class to the individuals of procedure class.

**Step 6: Create individuals**

The indicators of a specific pathway need individuals for classes like medicine, disorder etc. The choice of making a concept as individual or class depends on the context and the application. The ontology is developed with the goal of reusing it in other pathways. Hence pathway specific disease, activities and drugs are added as individuals. For example, Aspirin, Beta blockers are defined as individuals for class *Drug* and Unstable Angina (UA) is defined as individual of type *Acute Disease* class in the ontology.

### 4.3.2 Mapping of ontology concepts to SNOMED CT

In order to make the ontology align to a standard vocabulary and avoid the ambiguity in interpretation, the SNOMED CT identifiers are mapped to the concepts defined in the ontology. To improve the usability of the ontology, definitions for the class and subclass are provided through Protégé's documentation feature, and annotated it with SNOMED CT identifiers and definitions. Developing an automatic ontology mapping feature is beyond the scope of this thesis, hence the classes in the ontology is manually mapped to the concepts in SNOMED CT.

### 4.3.2 Extending the ontology

To extend this ontology for clinical indicators of another disease corresponding individuals has to be created and should be added to the ontology. For example, for representing the clinical indicator of cancer pathway, instances of drug, procedure, finding has to be added. Every concept in ontology will have a direct annotation with SNOMED CT. This should be enforced even while extending the current model to other

pathways to ensure that the model is completely reusable and designed to a common standard vocabulary.

### 4.3.3 Validation of ontology

The consistency and the correctness of the ontology are checked with the reasoner available in the Protégé. Changes in ontology are followed by running the reasoner several times to find out inconsistency in the ontology. Evaluation is carried out by using it in the specified application and then revising the initial ontology. The clinical pathway indicator set of five other pathways in Appendix B are checked to ensure that it can be represented in this ontology.

## 4.4 Formalization of indicators to SPARQL Queries

The indicators are formulated into SPARQL queries in this step. The data elements of the indicator are first expressed from the concepts defined in the ontology. The relation between data elements are constructed using the relations defined in the ontology. Further the logical constraints, time constraints and other exclusion criteria are formalized using the FILTER pattern in the SPARQL query. The denominator of a rate indicator is constructed by removing constraints that is applicable only to numerator. The formalization details of an example indicator to SPARQL query is described in section 5.3.

The method of formalizing quality indicators into SPARQL queries follows a series of steps according to Dentler et al (Dentler, Teije, Cornet, & Keizer, 2012). Rate based indicator involves a numerator and denominator and the numerator is a subset of the denominator. Therefore the numerator is formalized first with the constraints and the denominator is constructed by removing the constraints. The queries for the numerator and denominator are executed separately by running these queries over the patient data followed by the calculation of the rate. The formalization method of translating indicators from natural language to SPARQL queries consists of 7 steps.

1) Encode relevant concepts from the indicator by concepts from a terminology
2) Define the information model
3) Formalize time constraints and temporal relationships(FILTER)
4) Formalize number constraints (FILTER)
5) Formalize truth value constraints(FILTER)
6) Formalize inclusion and exclusion criteria(FILTER)
7) Construct the denominator by removing constraints that only aim at numerator.

## 4.5 RDF Data Model

The indicator value is measured by querying it on the patient data of the hospital. SPARQL is a query language for RDF graph. Hence the data has to be populated to an RDF data model for query processing. There are various specifications and tools which convert data from spreadsheet or relational data base to RDF data model. Once the data model is created, the SPARQL query engine can execute the query and show the results of the indicator.

## 4.6 Relational Database to RDF Mapping (RDB2RDF)

As compared to the relational data model, RDF is more expressive and data represented in RDF can be interpreted, processed and reasoned over by software agents. Most of the clinical data is stored in Relational Databases (RDB) in Hospital information system and are queried using SQL (structured Query Language). In order to use SPARQL for querying the data, the data from RDB has to be imported into an RDF data model. Here ontology acts as a data integrator tool.

There are different strategies and tools which implement the automatic conversion of relational data to RDF (Sahoo, et al., 2009). Lack of a common standard for these strategies led to an initiative by W3C called RDB2RDF Working Group. The RDB2RDF Working Group's mission is to standardize a language for mapping relational data and relational database schemas into RDF and OWL. Mapping is the process of converting database schema and instances to RDF dataset.

Two interrelated and complementary W3C standards are Direct Mapping of Relational Data to RDF and R2RML: RDB to RDF Mapping Language. Direct Mapping is a default mapping that automatically generates RDF from the relational data. R2RML is a mapping language where a user can customize which relational tables and columns get mapped to RDF using a specific vocabulary/ontology.

## 4.7 User Interface/ Web Front end

The user interface is the component in the architecture where the user can run the indicator, view the results of the indicator and modify exclusion/inclusion criteria. The implementation detail of each component in the architecture is further explained in section 5.6.

## 4.8 Identification of patterns and automatic query formulation

Clinical indicators of pathway are explored to identify common patterns so that they can be further classified into categories. They are classified into structure, process and outcome (Mainz, 2003). The process indicators are further classified based on drug related process of care and non-drug related process of care and these indicators are further analyzed to find a common pattern. Based on the research, two patterns for the definitions of indicator have been identified. The first pattern consist of *'who'*, *'what'*, 'when' and 'interval'. The keyword '*who*' specify the patient with a condition, *'what'* specifies the drug prescription or surgical procedure, '*when*' represents the time at which 'what' is happening and '*interval*' represents the time duration. Table 5 shows the indicators of unstable angina represented in the pattern. All indicators are for patients with unstable angina condition.

| Indicator | WHO | | WHAT | WHEN | INTERVAL |
|---|---|---|---|---|---|
| Aspirin prescribed at hospital discharge | Patients Unstable Angina | with | Aspirin | Hospital Discharge | |
| Beta blocker prescribed at hospital discharge | Patients Unstable Angina | with | Beta blocker | Hospital Discharge | |
| Aspirin within 3 hrs after hospital arrival | Patients Unstable Angina | with | Aspirin | Hospital Arrival | 3 hours |
| ECG within 10 minutes after hospital arrival | Patients Unstable Angina | with | ECG | Hospital Arrival | 10 minutes |
| PCI within 90 minutes after hospital arrival | Patients Unstable Angina | with | PCI | Hospital Arrival | 90 minutes |

**Table 5: Pattern 1, clinical indicator**

Another approach used is a pattern similar to graph pattern of RDF. The pattern consists of *'subject', 'property', 'type'* categories. The pattern for the sample indicator, patients with Unstable Angina who are prescribed Aspirin at Hospital Discharge is shown in Table 6.

| Subject | Property | Type | *Value* |
|---------|----------|------|---------|
| Patient | Has Disease | Disease | *Unstable Angina* |
| Patient | Has Undergone Procedure | Hospital Discharge | *x* |
| x | Has Prescription | Drug | *Aspirin* |

**Table 6: Pattern 2, Clinical indicator**

The added value of having a pattern for indicator is to define a new indicator based on the pattern. This will also eliminate the need of a SPARQL Query expert for formulating SPARQL queries for indicators. The strategy is to identify pattern from existing indicators and allow the user to select the corresponding value for the *subject, property, type* from a drop down list of the front end screen and use a query formulator component to generate SPARQL query on the fly. This will enable the framework to define new indicators from the user interface and generate corresponding SPARQL query dynamically. The implementation details are in section 5.5.

# 5.   Proof of Concept Implementation

The framework developed in last chapter is implemented and presented in this chapter. For the implementation, the performance measurement of indicators of clinical pathway of the disease 'Unstable Angina' is considered. The focus is on the clinical indicators since they provide insight into the quality of care provided.

Acute Coronary Syndrome (ACS) is the umbrella term for the clinical signs and symptoms of Acute Myocardial Infarction (AMI): unstable angina (UA), non–ST-segment elevation myocardial infarction (NSTEMI), and ST-segment elevation myocardial infarction (STEMI) (Daga, Kaul, & Manzoor, 2011). This is a high risk disease and leading cause of death all over the world which requires emergency evaluation and treatment. These three conditions differ with regard to duration, severity, and treatments. The patient's clinical history, presenting symptoms, biomarker levels, and electrocardiographic results are all evaluated to diagnose the condition. Clinical guidelines and protocols are used by healthcare professionals to decide on diagnosis, treatment and medications. In order to improve the quality of care, clinical pathways are introduced lately so that all patients are treated similarly and are managed with the optimal use of treatment. Since the treatment for UA is to some level predictable, the disease fits the requirements of a pathway and the performance monitoring of pathway can help in understanding the progress of pathway towards its goals.

The monitoring of UA pathway is done by measuring the indicators. Among the five domains of Leuven Clinical Pathway Compass, the automatic measurement of indicators in the clinical dimension is considered in this research since clinical indicators measures the quality of care. The European Society of Cardiology (ESC) guideline discusses a set of performance measures for ACS shown in Figure 16 (ESC Guidelines for the management of acute coronary syndromes, 2011).



- Use of aspirin
- Use of clopidogrel/prasugrel/ticagrelor
- Use of UFH/enoxaparin/fondaparinux/bivalirudin
- β-Blocker at discharge in patients with LV dysfunction
- Use of statins
- Use of ACE-inhibitor or ARB
- Use of early invasive procedures in intermediate- to high-risk patients.
- Smoking cessation advice/counselling
- Enrolment in a secondary prevention/ cardiac rehabilitation programme

**Figure 15: ESC guidelines performance measures**

The Canadian Cardiovascular Outcome Research Team (CCORTS) did an extensive research in the quality indicators for AMI (CCORT Quality Indicators, 2008) and presented a comprehensive list of structure, process, and outcome indicators for AMI. A summary of their indicator set is presented in Appendix A. Five indicators are selected from this list for the formal representation and for the demonstration of their measurement.

## 5.1 System Architecture of the performance measurement system

Figure 17 shows the system architecture of the performance measurement system. The three main components are the 1) ontology for the indicator, 2) web application and the 3) dataset.
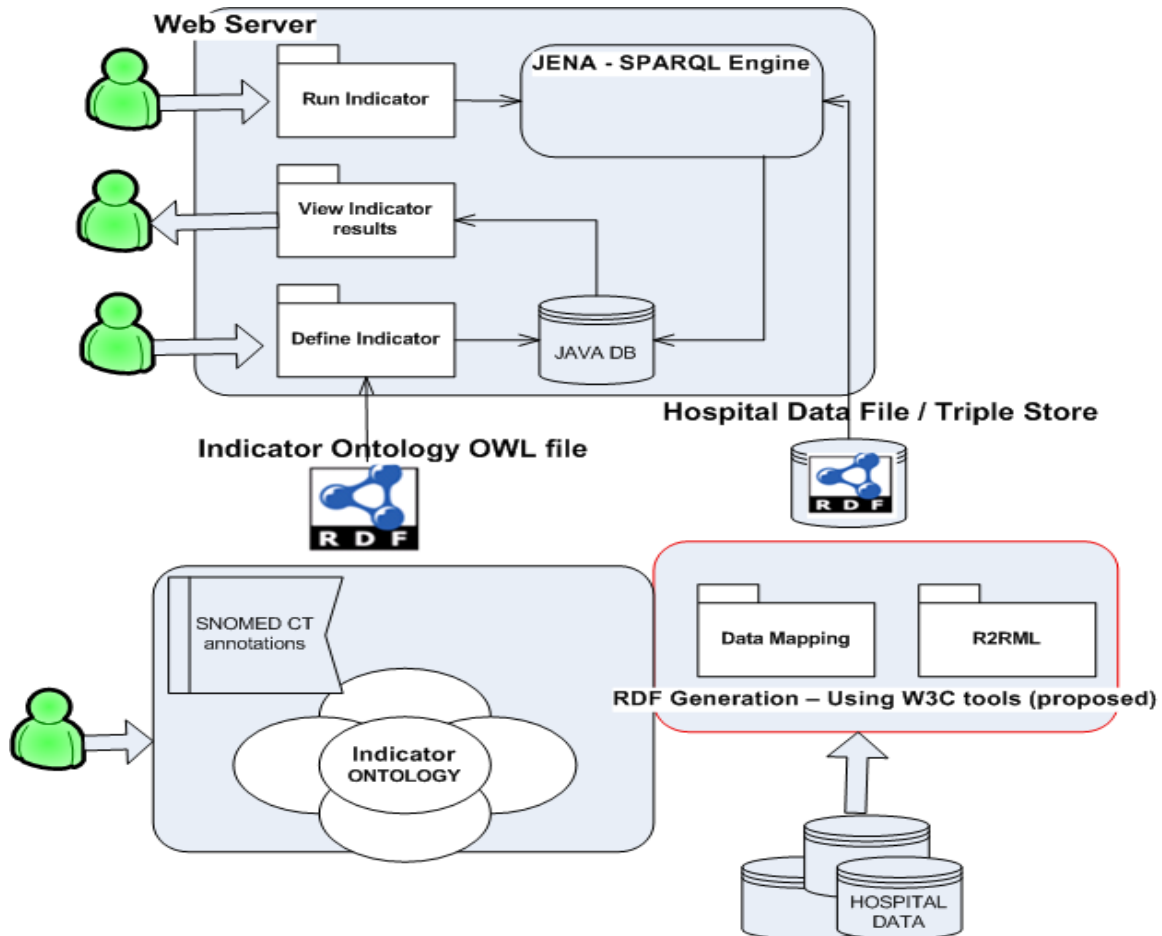


**Figure 16: System Architecture of the performance measurement system**

Ontology is developed in the ontology editor tool Protégé 4.3. The classes in ontology are manually mapped with the concept identifier in SNOMED CT. The data in the relational database (RDB) of the hospital has to be converted to RDF format and has to be stored in triple store. Triple store is the database for storing RDF triples. There are W3C recommended standards available to do the translation from RDB to RDF as already mentioned in section 4.6. A web application is developed to provide end users with the interface to run indicator, view results and define indicator.

## 5.2 Extending the ontology for Unstable Angina (UA)

Aspirin is beneficial because of its ability to reduce blood's tendency to clot in the blood vessels of the heart. Aspirin improves chances of surviving a heart attack and reduces the risk of recurrence in patients who have experienced a heart attack (ESC Guidelines for the management of acute coronary syndromes, 2011).

**Indicator definition**: Percentage of UA patients with aspirin prescribed at discharge
**Exclusion**:     Patients with Aspirin Allergy
**Numerator**:    All UA patients who had Aspirin at discharge
**Denominator**: All discharged UA patients

Concepts in the indicator are added as individuals to the ontology in the Protégé 4.3 tool shown in Figure 17. For example UA is added as an individual of Acute Disease class, aspirin is added as an individual of Drug class etc. The ontology is examined further whether the indicator can be defined using the properties specified in the ontology.

Steps followed:
1. Added Unstable Angina as an individual of type *Acute Disease*
2. Added Aspirin as an individual of type *Drug* in the ontology
3. Added Aspirin Allergy as an individual of type *Allergy*
4. Added *has Disease* as a property with domain *Patient* and range *Disease*
5. Added *has prescription* as a property with domain *Hospital Discharge* and range *Drug*
6. Added *has Allergy* as a property with domain *Patient* and range *Allergy*

To improve the usability of the ontology, definitions for the class and subclass are provided through Protégé's documentation feature, and annotated it SNOMED CT identifiers and definitions. Developing an automatic ontology mapping feature is beyond the scope of this thesis, hence the classes in the ontology is manually mapped to the concepts in SNOMED CT.
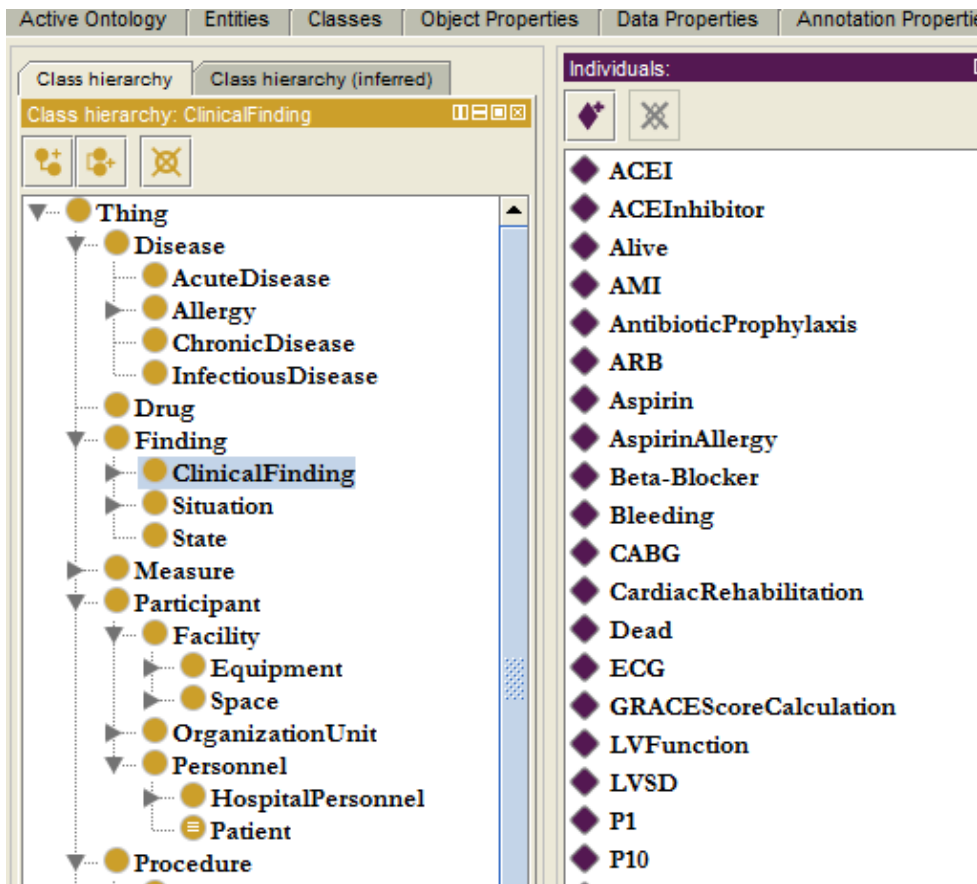
Figure 17 : Protege screen showing classes and individuals in ontology

In case of measuring variants of data elements, the data element can be declared as equivalent instance using owl:SameIndividual in the ontology. Unstable Angina and UA individuals are created and explicitly specified as 'same individual' to make the ontology reusable in a different context where these terms are used interchangeably.
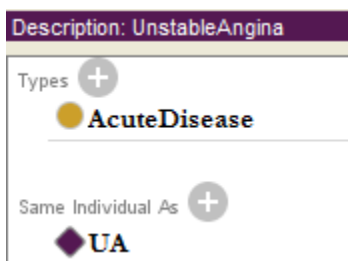


Figure 18: Same Individual feature in OWL

## 5.3 SPARQL Query formulation

In this section the formulation of indicator in SPARQL query is explained. The clinical indicator 'UA patients with Aspirin at discharge' are used here to demonstrate the query formulation. The method of SPARQL query formulation follows the step proposed by Dentler et al.

**Indicator definition**: Percentage of Unstable Angina patients with aspirin prescribed at discharge

**Exclusion**:     Patients with Aspirin Allergy

**Numerator**:    All Unstable Angina patients who had Aspirin at discharge

**Denominator**: All discharged Unstable Angina patients

Steps of query formulation

   1) Encode relevant concepts from the indicator by concepts from a terminology

This step is conducted by creating ontology and referring the concepts in the indicator with the ontology. The ontology implemented has a unique URI, automatically generated in protégé tool when the ontology is saved. A prefix is also created for this URI and used in the SPARQL query for referencing the concepts.

```
PREFIX cpci: http://www.semanticweb.org/ontologies/2013/6/cpci#
```
A prefix 'cpci' is created for the URI of the ontology and added as the first line in the query.

The URI for rdf vocabulary and its prefix is also added to use the rdf syntax in the query.
```
PREFIX rdf: http://www.w3.org/1999/02/22-rdf-syntax-ns#
```

   2) Define the information model

In this step, the relations between the concepts in the indicator definition are formalized. This is done by formulating a triple with the object properties. The variables in the query are preceded with a question mark.

Patients who has the disease Unstable Angina
```
?patient cpci:hasDisease cpci: UnstableAngina
```

Patients who are discharged
```
?patient cpci:hasUndergoneProcedure ?discharge.
?discharge rdf:type cpci:HospitalDischarge
```

All the discharged patients who got aspirin prescription
```
?discharge cpci:hasPrescription cpci:Aspirin
```

3) Formalize inclusion and exclusion criteria(FILTER)

This step is used to specify the exclusion criteria. Patients who got Aspirin Allergy are filtered out in this step

```
FILTER (NOT EXISTS {?patient  cpci:hasDisease   cpci:AspirinAllergy})
```

4) Construct the denominator by removing constraints that only aim at numerator

Using this same approach, denominator of the indicator is formulated. Here denominator consists of all discharged patients with Unstable Angina.

```
?patient cpci:hasDisease cpci: UnstableAngina
?patient cpci:hasUndergoneProcedure ?discharge.
?discharge rdf:type cpci:HospitalDischarge
```

In order to find the number of distinct patients in the result set, the aggregate function 'count' is used in the select statement of the query. The numerator and denominator are executed separately and the percentage is calculated automatically.

**NUMERATOR**: Number of patients with Unstable Angina who are prescribed Aspirin at discharge

```
PREFIX rdf: http://www.w3.org/1999/02/22-rdf-syntax-ns#
PREFIX cpci: http://www.semanticweb.org/ontologies/2013/6/cpci#

SELECT   (COUNT (DISTINCT   ?patient) AS ?count)

WHERE {
      ?patient    cpci:hasDisease    cpci:UnstableAngina.
      ?patient    cpci:hasUndergoneProcedure    ?discharge.
      ?discharge   rdf:type             cpci:HospitalDischarge.
      ?discharge   cpci:hasPrescription   cpci:Aspirin.

FILTER (NOT EXISTS {
      ? patient   cpci:hasDisease    cpci:AspirinAllergy})}
```

**DENOMINATOR**: Number of discharged patients with Unstable Angina

```
SELECT   (COUNT (DISTINCT   ?patient) AS ?count)
WHERE {
      ?patient   cpci:hasDisease   cpci:UnstableAngina.
      ?patient   cpci:hasUndergoneProcedure    ?discharge.
      ?discharge rdf:type           cpci:HospitalDischarge.
FILTER (NOT EXISTS {
      ?patient   cpci:hasDisease   cpci:AspirinAllergy})}
```

## 5.4 Data Preparation

In order to verify the SPARQL query, a dataset of patients are prepared in Excel spreadsheet manually. This excel file is then translated to RDF file using a tool called Open Refine (ex-Google Refine). Open Refine is a standalone open source desktop application for data cleanup and transformation to other formats (Open Refine, 2013). The mapping between the columns in the excel file and the classes in ontology is specified using the mapping file in the tool. After the mapping, the excel file is exported as an RDF file.

## 5.5 Web Application

A web application has been developed using Java Enterprise Edition (JavaEE) specifications to run the indicator and show the results in a user interface. The NetBeans integrated development environment (IDE) is a free, open-source IDE for developing Java applications, including enterprise applications. The NetBeans IDE is used to develop the web application and JSF (Java Server Faces) is used to develop the web pages.

Jena API is used in the application to process the RDF data. Jena is a Java framework for the creation of applications of the semantic web developed by HP Labs. It provides interfaces and classes for the creation and manipulation of RDF repositories and OWL based ontologies. Jena provides RDF API, OWL API and SPARQL Query engine. The RDF API provides classes and interfaces of every important aspect of RDF specification and the OWL API provides classes/interfaces to represent all aspects of the OWL language.  The Model Factory class in Jena is used to create a model of the ontology using the ontology file created. The model created will read the input dataset created in RDF. Jena also provides methods for the execution of SPARQL queries. Jena uses the ARQ engine for the processing of SPARQL queries.

JSF is used to create the web pages for running the indicator queries, viewing the results and for defining new indicators. The application is deployed in the Glassfish web server available in Netbeans IDE. A Java DB is also used to store the results of the indicator in each run. The application is started by running it from the Netbeans IDE.

The homepage of the application shows indicators already stored in the application. User can run, modify and schedule the indicator to run from this screen. When the user runs the indicator from the front end screen, corresponding query is executed and the results are shown in the front end screen and also stored in the database. The criteria of existing indicator can be modified by clicking the modify button in the web page.

**Figure 19: Existing indicators in the system**

When the user click the run button for the existing indicator, the SPARQL query of the corresponding indicator is run against the RDF data and the results are showed in the result screen. The result screen also shows the history of indicator results stored in a database inbuilt with the application.



**Figure 20: Indicator results screen**

When the user want to define a new indicator, he will select the criterion of the indicator from the drop down list in the define indicator screen. The concepts in the drop down list are populated based on the concepts in the ontology.



**Figure 21: Indicator definition using dropdown list**

## 5.6 Validation of the system

The implemented performance measurement system is validated using some random clinical indicators of the stroke pathway. For example, the concepts in the indicator, proportion of patients with warfarin at discharge can be represented using the ontology class by adding warfarin as an individual (instance) of drug class and querying for those patients who had warfarin at discharge. However, for indicators like proportion of patients with unscheduled return to intensive care unit, the concept unscheduled return cannot be represented using the current ontology. A possible solution is to add unscheduled return as an individual to the situation class in the ontology and query those patients who has finding 'unscheduled return'. In that case, an identifier has to be added for 'unscheduled return' in the patient record for data selection.

# 6.   Discussions

In this chapter a number of findings and suggestions are presented which were learned in the course of the research.

Investigating the potential of semantic web technologies towards automation of performance measurement is the prime focus of the research. One of the main challenges in healthcare domain is the lack of uniformly structured data. Semantic web technologies: RDF and OWL offer the potential to simplify the management of these heterogeneous data. However, being a relatively young technology, there are gaps in standards and implementations which pose some technical limitations.

## *SPARQL query advantages*

The main advantage of SPARQL over other database query like SQL (Structured Query Language) is the ability to federate queries across different repositories. This is made possible by the RDF framework. Therefore using a single SPARQL query, application can query appropriate data source.  In case of SQL, multiples queries have to be written to extract relevant data with complex table joins and again develop software code to process the data.

## *SPARQL Query Limitations*

Even though representation of indicators in SPARQL queries is a useful method to formalize indicators, SPARQL query does not support arithmetic operations on date time by default. This is a serious limitation since measurement of time duration between activities in the pathway is a critical indicator for checking the performance of the pathway. However custom functions can be developed in SPIN (SPARQL Inferencing Notation). SPIN is a standard to represent SPARQL rules and constraints on semantic web. It provides ready to use library of common functions and allows users to define their own SPARQL functions and query templates (Knublauch, Hendler, & Idehen, 2013). Therefore date time difference functions can be created in SPIN and used in SPARQL expression.

## *Reasoning capabilities*

The standard definition of indicators using semantic queries avoids ambiguity and therefore error in measuring the indicators. The ontology provides a model of the domain of indicators and can be utilized to measure indicators of any pathway. Unlike UML, because of the machine processable capabilities of ontologies, applications can directly

use the ontology. And this ontology can be reused and can extend other ontology .The description logic foundation of ontology enables the use of reasoning which is an added value of ontology. Reasoner is a piece of software program which can infer logical consequences from a set of asserted facts. The reasoner along with SWRL (Semantic Web Rule Language) can helps in querying complex relationships in the ontology.

### *Flexibility to reuse*

The flexibility of easily changing the schema compared to the rigidity of relational database is a key feature of the ontology. Adding a new class or subclass in the ontology is a mere extension unlike deleting the schema and creating a new schema in relational database.

### *Reuse of the framework in hospital information system*
The ontology of clinical indicator captures the basics concepts in clinical indicator like disease, procedure, drug, finding and temporal aspect. Individuals are added considering the use case of unstable angina pathway. For a different pathway, the core model of the ontology can be reused and if necessary can be extended by adding more individuals and map it to SNOMED CT.

### *Extracting the patients who followed the pathway*

The framework does not explicitly guarantee the extraction of patients who really followed the pathway. In future, in order to use this framework, methods for relevant data extraction are proposed in this section. Each pathway can be given a unique identifier and every patient who follows the pathway can be given this identifier. Based on this identifier, the patients can be extracted.

Giving entry criterion for every pathway and extracting only those patients who fulfill those criteria can be a method to identify the patients who followed the pathway. This might need a classification technique in which first a training set of patients who followed the pathway are collected and identify the criterion (attribute values). Eg: if the compulsory criterion set for patients who followed the pathway are diagnosis x, treatment y, then a classification model can be built with these attribute values. This classification model can be used for predicting whether a test set of patients has followed the pathway or not.

Another potential method would be finding a relation between DBC codes and clinical pathways. Diagnosis Treatment Combinations (DBC) is a classification code which represents the sequence of medical activities that are performed during the treatment of a

patient (Westerdijk, Zuurbier, Ludwig, & Prins, 2012). A DBC code consist of three attributes – diagnosis, treatment and type of care. But for a single DBC code there can be different combinations of activities. Each activity group has to be further analyzed for finding a relation between activity group and clinical pathway.

Designing simulation models of clinical pathway and execute it with input sets of data can be used to identify the patients who have followed the pathway.

# 7. Conclusions

*Summary*

Performance monitoring of pathway is inevitable in clinical pathway management which is made possible by measuring the indicators of pathway. Automating the measurement of these indicators will reduce the effort and time consumption required for calculation. In order to do this, it is important to represent the indicators with no ambiguity of interpretation and this will enable the calculation of their values in a coherent way.

In this research, a framework for measurement of indicators is developed and implemented using an 1)ontology for indicators, 2)an RDF model for data, 3) identification of a  pattern for indicators, 4)a parser for interpreting the keywords expressed as selections in drop down list and a translator for converting this into semantic queries for automating calculation. The proposed framework is implemented using a web based solution which will enable the user to automatically calculate the indicator with the click of a button, view the results and do a comparison of the history of results stored during each run. Furthermore, it will provide the users with no expertise in query formulation with an interface to define new indicators or modify criteria of existing indicators by selecting keywords from a drop down list. The frame work achieves the challenge of generating query on the fly corresponding to an indicator and provides the results for analysis.

*Limitations*

One of the limitations of the research is not using an original database of the hospital to demonstrate the potential of semantic technologies in using heterogeneous data. The main reason was the difficulty in getting the data from the hospital on time. Furthermore, the emphasis was given on designing and implementing the framework for indicator definitions using ontology and semantic queries.

*Future work*

The next step will be to use this framework in a hospital where clinical pathway is used. Another useful future work which contributes to the performance monitoring of pathway is extending the ontology to other domains (financial, team, process, service) of pathway indicators.

*Conclusions*

Semantic web technologies can immensely provide communication and knowledge sharing between disparate systems. The application of semantic technologies in the hospital will provide IT systems with the ability to exchange and process data automatically. Healthcare domain can benefit since these technologies can facilitate the aggregation of heterogeneous data using explicit semantics, representation of these data in a well- defined model, reuse of data and inference of knowledge from data using logic.

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# Appendix A

Indicators of quality of care for patients with acute myocardial infarction

| | |
|---|---|
| **In hospital process of care indicator – Pharmacologic** | Aspirin prescribed at hospital discharge |
| | Aspirin within 24 hours before hospital arrival or within 3 hours after hospital arrival |
| | Beta-Blocker prescribed at hospital discharge |
| | Angiotensin-converting-enzyme (ACE) inhibitor or angiotensin-receptor blocker prescribed at hospital discharge |
| | Statin prescribed at hospital discharge |
| | Fibrinolytic therapy within 30 minutes after hospital arrival |
| **In hospital process of care indicator – Non Pharmacologic** | ECG within 10 minutes after hospital arrival |
| | Primary percutaneous coronary intervention within 90 minutes after hospital arrival |
| | Reperfusion therapy in eligible patients with ST-segment elevation myocardial infarction |
| | Risk stratification (i.e., cardiac catheterization, exercise stress testing, perfusion imaging or stress echocardiography) |
| | Left ventricular function assessment |
| | Smoking cessation advice, counseling or therapy during hospital stay |
| | Referral to cardiac rehabilitation |
| Outcome Indicator | In-hospital mortality |
| **System Indicator** | Fibrinolytic therapy within 60 minutes after call for emergency medical services |
| | Primary percutaneous coronary intervention within 120 minutes after call for emergency medical services |
| | Pre-hospital 12-lead ECG |

Appendix to Tu JV, Khalid L, Donovan LR, et al; Canadian Cardiovascular Outcomes Research Team / Canadian Cardiovascular Society Acute Myocardial Infarction Quality Indicator Panel. Updated indicators of quality of care for patients with acute myocardial infarction. CMAJ 2008;179(9):909-15.

# Appendix B

**The clinical pathways indicator set** (Panella, Marchisio, & Di Stanislao, 2003)

| Clinical pathway | Indicator | Typology | Measure |
|---|---|---|---|
| Inguinal hernia repair | Average length of stay | Process | No. of days |
| | Rate of day surgery activity | Process | Percentage |
| | Median of preoperative exams | Process | No. per patient |
| | Proportion of patients with antibiotic prophylaxis consistent with current recommendations | Process | Percentage |
| | Proportion of patients with correct hair removal | Process | Percentage |
| | Rate of completion of clinical records | Process | Percentage |
| | Proportion of patients with massive bleeding | Outcome | Percentage |
| | Proportion of patients with postoperative pain | Outcome | Percentage |
| | Proportion of patients with wound infections | Outcome | Percentage |
| | Proportion of patients with unscheduled return to operating room | Outcome | Percentage |
| Stroke | Proportion of patients with length of stay >2 hours in emergency room | Process | Percentage |
| | Average length of stay | Process | No. of days |
| | Proportion of patients with early rehabilitation (within 3 days from acute event) | Process | Percentage |
| | Proportion of patients treated with nifedipine | Process | Percentage |
| | Proportion of patients with warfarin at discharge | Process | Percentage |
| | Proportion of patients with antithrombotic at discharge | Process | Percentage |
| | Rate of completion of clinical records | Process | Percentage |
| | Proportion of patients with unscheduled return to intensive care unit | Outcome | Percentage |
| | Proportion of patients with improved Barthel Index at discharge | Outcome | Percentage |
| | Total in-patient mortality | Outcome | Percentage |
| Chronic renal failure | Average length of stay | Process | No. of days |
| | Levels of appropriateness of the stay with AEP protocol | Process | Percentage |
| | Proportion of patients with temporary access at the first dialysis | Process | Percentage |
| | Proportion of patients with permanent catheters in dialysis population | Process | Percentage |
| | Proportion of patients with infection to arteriovenous fistula | Process | Percentage |
| | Rate of completion of clinical records | Process | Percentage |
| | Proportion of patients with discharge instructions | Process | Percentage |

| Clinical pathway | Indicator (activity, diet, etc.) | Typology | Measure |
| --- | --- | --- | --- |
| | Proportion of patients with programmed discharge | Process | Percentage |
| | Minimum success rate (MSR) in dialysis patients | Outcome | MSR score |
| | Total in-patient mortality | Outcome | Percentage |
| Heart failure | Rate of diagnostic agreement between emergency room and general medicine unit | Process | Cohen's kappa |
| | Average length of stay | Process | No. of days |
| | Rate of completion of clinical records in emergency room | Process | Percentage |
| | Rate of completion of clinical records in general medicine unit | Process | Percentage |
| | Proportion of patients with left ventricular function assessment (LVFA) | Process | Percentage |
| | Proportion of smoker patients with advice/counselling for smoking cessation | Process | Percentage |
| | Proportion of patients with written discharge instructions addressing: activity level, diet, discharge medications, follow up, weight monitoring, and what to do if symptoms worsen | Process | Percentage |
| | Proportion of patients with ACE inhibitor (ACEI) at discharge | Process | Percentage |
| | Rate of unscheduled readmissions within 31 days | Outcome | Percentage |
| | Total and specific in-patient mortality (stratification according to severity of patient's condition at admission measured with New York Heart Association score) | Outcome | Percentage |
| Total hip replacement | Average length of stay | Process | No. of days |
| | Average diagnostic accesses of the patients | Process | No. per patient |
| | Median of preoperative exams | Process | No. per patient |
| | Proportion of patients compliant with preoperative analgesic therapy | Process | Percentage |
| | Proportion of patients with preoperative administration of erythropoietin | Process | Percentage |
| | Proportion of patients with antibiotic prophylaxis consistent with current recommendations | Process | Percentage |
| | Proportion of patients with early complications | Outcome | Percentage |
| | Proportion of patients with late complications | Outcome | Percentage |
| | Average level of residual disability at follow up | Outcome | FIM scale |
| | Proportion of patients with complete follow up | Process | Percentage |