Systems engineering approach to healthcare performance analysis

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Abstract: The objective of the paper is to present a method for analysing the performance of a territorial healthcare system. The proposed method has been developed by using the main concepts of the maintenance service of production systems, and transferring them into the healthcare services. To this aim, significant analogies have been recognised between a basic strategy for production system maintenance and the main actions to be done for patient healthcare. Based on this analogy, main key performance indicators (KPI) in industrial maintenance have been directly related to KPIs in healthcare. Then, a transfer of industrial maintenance actions, described by a specific ontology, has originated a corresponding ontology of main healthcare activities at the level of a territorial healthcare service system. The resulting ontology has been applied as a guide in conducting the analysis of the characteristics and performance of a regional healthcare system.

Keywords: healthcare system; process maintenance; performance evaluation; key performance indicator; KPI; essential level of assistance.


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Salvatore Roberto Lo Turco began his activities as a Computer Programmer Analyst. He is specialised in software maintenance. He worked for IBM, dealing with goodwill and project management. He realised information systems interconnected. In the health sector, he was responsible for information systems and he created the organisational structure of IT sector at THA of Asti. Currently, as a freelancer, he is responsible for integration and support issues on the protection of personal data. He has been teaching courses in management and protection of personal data. He created the first national database of information on the processing of personal data.

1 Introduction

The system of healthcare services includes all the organisations, institutions and resources whose primary objective is to promote, maintain and restore health (WHO, 2000). The complexity of the system and the number of interactions among the various components make the analysis of a health system a very complex and not yet solved issue. Evaluating the performance of a health system involves two key issues: the first is to assess whether the healthcare system, as it is organised, is able to reach its objectives and the second is to compare achievements with what the system is capable to do (Tyge Payne and Hoffman, 2012). The World Health Organization (WHO) has established the basic principles that the national healthcare systems of the member states must assure to citizens. The fundamental principles are accessibility, equity, sustainability and quality of delivered services. Assuring the respect of these principles it is possible to reach the objective of improvement of the health status of the population (Metzler et al., 2008). The healthcare system must ensure the fulfilment of the demand for healthcare. The healthcare demand is strictly related to territorial peculiarity that can influence the answer of the system. In order to guarantee an essential level of offered healthcare services for all citizens, in Italy, the decree of the President of the Council of Ministers of 29 November 2001, defined the essential levels of assistance (ELA) that establish the health services guaranteed by the national health service (DPCM, 2001). The status of health, is, also, strongly influenced by other aspects such as the level of education, economic independence, the health of the environment (Marmot, 2006). The performances of the educational system, the environmental protection and the economic growth of a state,
even if they do not have as their main objective the improvement of health status, are important influences on outcomes (Institute of Medicine, 1997).

The need and importance of the evaluation of the performance of a health system cannot be fully satisfied without a model that guides the analysis and the performance evaluation (Murray and Frenk, 1999) taking into account all the aspects that influence performances.

The analysis of complex systems is a well-known topic in industrial environment. For industrial systems, modelling techniques have been developed in order to give a correct evaluation of the system and support the managers in the decision making process (Villa, 2006). The engineering education received and the experience in modelling of industrial networks gained in the European project collaborative demand and supply network (CODESNET) (Villa and Taurino, 2011; Villa et al., 2012), allowed to mature knowledge, with a sufficient level of confidence, in the definition of models that can describe industries (Antonelli et al., 2006). In this paper, we introduce a model for the health services system through an analogy with the function of maintenance of processes. Having explained the conceptual analogy, the tools used for modelling in industrial environments are adapted to the modelling of the healthcare system, introducing in this way an ontology that can be used as a guide in the analysis phase. The conceptual analogy was then transferred on key performance indicators (KPIs) used to measure performance in their respective fields, in order to provide immediate guidance in the analysis.

Finally, the performance of a health system linked to a territorial healthcare agency (THA) in north of Italy is analysed. An analysis of the population has been conducted in order to identify those determinants of educational, socio-economic and cultural development that may affect the performance of the healthcare system (Millet et al., 1994). To complete the analysis, the consumption of each type of service is analysed in order to provide guidance on the allocation of new services or logistical reorganisation of existing ones. The performance indicators have been calculated on the average behaviour of the system knowing that the healthcare system differs from other social systems for the high variability and unpredictability of events. Faced with a state of health almost similar between two individuals, their interaction with the system and their responses to treatment can be very different. Furthermore, despite the various types of preventive interventions with the aim of reducing as much as possible incidence of disease, the unpredictability of developments on health status remains one of the major difficulties faced in the healthcare system.

The analysis was performed on the database of the Asti THA; available since its participation to the research project of national interest (PRIN, 2008) “innovation of healthcare systems by supply chain management techniques” data are referred to the year 2007.

In this paper, Section 2 introduces the conceptual analogy between the health’s services and the process maintenance and their respective models. In Section 3 the correspondence on KPIs is proposed. In Section 4 there is a description of the source of data used for the analysis presented in Section 5. The conclusions are given in Section 6.
2 Conceptual analogy between health’s services and the process maintenance

The purpose of this section is to show that a strong analogy between process maintenance and health services exists. The conceptual analogy has been found starting from the definition of maintenance and healthcare service given, respectively by the Organization for Economic Co-Operation and Development (OECD) and the WHO.

The OECD has defined maintenance like the function that has to constantly control production plants and all the necessary work activities that can assure the smooth operation of the system and the good conditions of production facilities, services and equipment for plants (Cattaneo et al., 2007). Maintenance is the science, which finalises the human activities to a sustainable and economical use of resources in the design and management of systems. This concept is largely applied in every human context: we can speak of maintenance of a structural work, maintenance of a natural environment, maintenance of a service, maintenance of a process, maintenance of a product, maintenance of a health status.

By applying the process maintenance definition to a specific process, maintenance is referred to the whole set of activities that can assure a proper usage of the process by the user and to reach the goals of effectiveness, efficiency in their present operating context.

The WHO has defined health like the state of complete physical, mental and social well-being and not merely the absence of disease or infirmity (WHO, 1946). Health is the fundamental right of the human being. All the National States are obliged to take responsibility to identify and change the factors that contribute negatively on the collective health while promoting those favourable. In this context, the health it is not only the goal but also a resource that allows people to lead a daily life that is productive on an individual, social and economic-base. The national healthcare system is constituted by the whole set of functions, services and activities dedicated to the promotion, the maintenance and the recovery of the physical and mental status of a person with no distinction due by individual or social conditions and with an equal treatment for all citizens (WHO, 2000).

In Table 1 the analogy between the two definitions, where the maintenance definition is considered applied to the specific concept of process maintenance, is schematically summarised.

<table>
<thead>
<tr>
<th>Process maintenance</th>
<th>Healthcare service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is a function that has constantly to control process’ usage.</td>
<td>Is a function that has constantly to control the health status of persons.</td>
</tr>
<tr>
<td>Is a function which has constantly to control the whole set of works for repairing and reviewing.</td>
<td>Is a function that has constantly to identify, control and change the whole set of factors that adversely affect the collective health.</td>
</tr>
<tr>
<td>Is a function that has to assure the proper operation of process.</td>
<td>Is a function that has to assure the promotion of favourable factors that improve the health conditions of persons.</td>
</tr>
<tr>
<td>Is a function that has to assure the good performance of the process.</td>
<td>Is a function that has to assure the maintenance of a good health status for persons.</td>
</tr>
<tr>
<td>Maintained process can achieve the specific goals of effectiveness, efficiency and economy.</td>
<td>Healthy persons can lead a daily life productive on an individual, social and economic-base.</td>
</tr>
</tbody>
</table>
Considering the two definitions, it is easy to recognise the analogy in terms of objective, they both have to improve or adjust something and in terms of actions, they both can use prevention, control and recovery.

The analogy can be also transferred on a modelling point of view in order to have a formal model that can guide during the analysis of the systems. In the next sub-section, a model of the process maintenance activities is introduced.

**Figure 1** Process maintenance scheme
2.1 Model of process maintenance activities

In literature, models for the maintenance function can be found in works concerning the product lifecycle management (Matsokis and Kiritsis, 2010). In the documents of the European project, amePLM (advanced platform for manufacturing engineering and product lifecycle management – http://www.ameplm.eu/), is proposed an ontology model for the process maintenance activities. Starting from this ontology model the next scheme for the process maintenance activities is derived and shown in Figure 1.

The scheme illustrates the relationships among all the activities described by the ontology. In particular, the operations in the user’s context are the activities of the process that must be performed in its context. The process assessment is the control and validation of the process. The process upgrade is a renovation of process characteristics in order to improve its performances. The process recall is the correction of important defects on process execution.

The skilled human resources, that interact each other and exchange information in a structured way, execute all the activities in the maintenance function. The actors who perform the process maintenance function are the Process manager and the Maintenance’s manager responsible, respectively, of the process planning and control and of the coordination and execution of the maintenance related activities. Activities in the operation user context require documents like the process usage manual, detailed process specification and process maintenance manual.

Those reports and documents contain data and information that are necessary for the activity owner to work. The activity results must be collected in other documents in order to constitute the input information for those activities that require them.

In the industrial sector a way to evaluate the performance of a production system is to identify a set of KPIs. The set of KPI can provide quantitative information useful to assess the achievement of the objectives for which the system was created, and the level of its performance. In the field of management of supply chain systems, the Supply Chain Council has developed a metric, called SCOR (https://supply-chain.org/), to measure the performance of a production system (Simchi-Levi et al., 2008).

In the next sub-section the modelling approach adopted for the process maintenance function is transferred to the healthcare services.

2.2 Model of healthcare services activities

The healthcare service function includes activities that represent actions done by the healthcare system, on a specific territorial area, in order to reach the objective of improvement of the health status.

To identify those activities the model of the process maintenance function is used and a transfer of concepts from the industrial context to the healthcare system is proposed in the scheme in Figure 2.

The scheme put in evidence that the healthcare services must take into account the territorial conditions and people life style, so the first action needed to supply the right services is an analysis in the socio-economic context. The input for this analysis contains data and information about the social conditions, the economical characteristic of population and their life style. The output of this analysis is reported in the socio-economic context report containing KPIs on the determinants of the health status. The output of the health status analysis collects information about the population health
status with KPIs on the healthcare demand. The THA’s manager uses the outputs of the two previous analyses to identify a strategy of prevention and to plan the resource allocation on the territory.

Figure 2  Healthcare service scheme model
The healthcare is the service supplied by doctors to preserve good health conditions of a person or population or to improve the health status with the available tools and care’s procedures.

A specific analysis is required for chronic patients affected by diseases of long duration and, generally, slow progression.

The outcome is quantified, respectively, by set of KPI of effectiveness and by a set of KPI on the chronic diseases. In the next section the analogy has been transferred on a KPI correspondence between the industrial application of performance analysis on the process maintenance function and the analysis of a territorial healthcare system.

3 KPI’s correspondence

The SCOR metrics is largely used in the industrial systems analysis. It contains sets of KPI useful for the performance analysis. The selected SCOR’s KPI have a correspondence with KPI of the healthcare system.

KPI that can describe the characteristics of the population are classified as KPI on health determinants, like the indicators of the population size, the average age, the average socio-economic level. KPIs that can describe the demand of health are the number of requests of healthcare services weighted with the service’s cost.

Health services are provided to the population on the basis of three different levels of care (Declaration of Alma-Ata, 1978).

The first level of care (primary healthcare) is the first contact between the health system and the citizen and must be accessible to all. The performances that belong to this level of care include prevention, maternal and childcare, control on safety of water and food, prevention through vaccination and education on specific risks or diseases. Qualified personnel who do not have the first contact with the citizen and who intervene for acute cares for short periods provide the second level of care (secondary healthcare).

The two lists of KPIs are reported in Table 2.

In such treatments are included outpatient services provided by medical specialists, and services provided by the hospital emergency department. The third level of care (tertiary healthcare) includes all services that must be provided within the hospital to inpatients. For each level of care KPIs that describe the demand of services are defined in terms of ELA.

KPIs on chronic diseases represent important performance indicators of the system, trends can give information about the prevention function of the system and the number of patients with chronic diseases and the typology of diseases can give information about the future healthcare services demand and costs.
### Table 2  
KPIs correspondence

<table>
<thead>
<tr>
<th>KPI healthcare</th>
<th>KPI SCOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>KPI on health determinants</td>
<td></td>
</tr>
<tr>
<td>Population</td>
<td>Market evaluation</td>
</tr>
<tr>
<td>Socio-economic condition</td>
<td>Market characteristics</td>
</tr>
<tr>
<td>Average age</td>
<td>Expected product life</td>
</tr>
<tr>
<td>KPI on health demand</td>
<td></td>
</tr>
<tr>
<td>Average DRG</td>
<td>Cost per good unit product</td>
</tr>
<tr>
<td>Hospital admissions</td>
<td>Productivity rate</td>
</tr>
<tr>
<td>Average hospitalisation</td>
<td>Standard processing time</td>
</tr>
<tr>
<td>Access to healthcare</td>
<td>$N^o$ products/services produced $=$ volumes</td>
</tr>
<tr>
<td>Trend of access to healthcare</td>
<td>Sales trend of each product/service</td>
</tr>
<tr>
<td>KPI on effectiveness</td>
<td></td>
</tr>
<tr>
<td>Turnover index</td>
<td>Inventory turnover</td>
</tr>
<tr>
<td>Occupancy rate of beds</td>
<td>Increase/decrease of inventory</td>
</tr>
<tr>
<td>% incidence of ordinary activity</td>
<td>$n^o$/% standard items</td>
</tr>
<tr>
<td>Patients satisfaction</td>
<td>Customer satisfaction i.e., sales amounts</td>
</tr>
<tr>
<td></td>
<td>$N^o$ of customer complaints</td>
</tr>
<tr>
<td>% adherence to regional standards</td>
<td>Time to process an order</td>
</tr>
<tr>
<td></td>
<td>On-time deliveries</td>
</tr>
<tr>
<td></td>
<td>$N^o$ of late orders</td>
</tr>
<tr>
<td>Waiting time/waiting list</td>
<td>Production lead time</td>
</tr>
<tr>
<td>Waiting time reduction</td>
<td>Currentness e.g., elimination of backlog</td>
</tr>
<tr>
<td>KPI on chronic diseases</td>
<td></td>
</tr>
<tr>
<td>% of population with chronic diseases</td>
<td>% of defected product</td>
</tr>
<tr>
<td>Drugs consumption from chronic patients</td>
<td>Costs for reprocessing</td>
</tr>
</tbody>
</table>

## 4 Source of data

In Italy, the THA has a huge amount of data about the supplied services and the flow of patients in the healthcare system.

These data are a precious resource for analysts in order to analyse the structure of the health system, to evaluate its performances, to plan the investment allocation and to determine and monitoring costs (Tekieh et al., 2015). The THA collects data in a standard format, the same format in each THA, in Italy. Thanks to the standards of data collection, the database construction and the analysis is replicable at the same way in each THA both on regional or national levels by considering set of THAs. Data are collected from the national health system in a standardised framework by periodic flows of data, scheduled in specific days of the year for each sub-service. Collected data have been organised and stored in a database and are at disposal of the THA's managers for internal analysis that can support the strategic and decision making processes.
The construction of the database is a big issue because of the high amount of data, often redundant and not easily accessible (Sondik, 2008). The available data concern six different services with a different database for each one: data concerning patients’ admission and hospital discharge; data concerning the emergency department; data concerning the delivered ambulatory care services for inpatients; data concerning delivered ambulatory care services for outpatients; data concerning the consumption of medicines; data concerning the assistance of patients at home or in specific nursing home.

For all of these databases, data are of two kinds, personal and clinical, stored into two different tables.

The original format of data is a textual format, so, firstly, all data were collected in a MySQL database by means of a php routine to automatically import data. Furthermore, the personal and clinical sections were merged and elaborated to address the following issues: remove redundancy, anonymising data, improving query performances and optimising large scale reporting.

Data collected in the database concerns services supplied and patients that live in a big area that cover a province of the north of Italy.

The analysis has the goal to put in evidence the performance of the THA in the main city of the considered province. The results of the analysis can support the THA’s managers in the management. Thanks to the standard procedure for the final database’s creation, replicable at the same way in every Italian THA, the same analysis can be replicated in other THA, in sets of THA or at a national level.

In this study, a database consisting of five million of records and 113 fields was built. Each record corresponds to a single service used by the patient in a specific day and into a particular healthcare centre. To the same patient can be associated more than one record. For each health service all the information about the kind of service provided, the personal and clinical data about the patient and the data concerning the service provider are recorded in the database. The dimension can give an idea of the amount of healthcare data that must be managed in order to be easily accessible with queries with high informative power. The collected data refer to the entire year 2007.

5 A territorial healthcare service analysis

The performance of a health system are strongly influenced by regional characteristics and peculiarities that must be taken into account in the assessment phase and even more when comparing different territorialities (Metzler, 2007). WHO identified the determinants of health, i.e., those features that influence health system performance and the demand of health services. In order to provide a description of the population in terms of determinants of health, an important information to allocate the healthcare services is to have data about the distribution of population in the territory. Maps have been often used in order to identify area with specific and serious diseases (Bell, 2006) but they represent an useful instrument also to have an immediate interpretation about distribution of KPIs on an area (MacEachren, 1995).
Figure 3  Population distribution (number of habitants) (see online version for colours)

Figure 4  Average age distribution (see online version for colours)
In this work a map representation of the KPIs values in the analysed area is used, by dividing into six districts the city area. In Figure 3 a map that represents the population distribution in the city is shown, the central red zone represents the area with the less number of habitants (between 2,493 and 2,627 habitants, as reported in the legend) but with more density since the surface is very small, while the blue zone represents the area with the most number of habitants (between 3,163 and 3,298) but lower density since the surface is bigger.

In Figure 4, the average age of population in each district is represented on the map. The average age of the population is almost uniform in the city, the interval is from 53 to 56 years, so, the health requirements from each area of the city do not depend by the average age of the population that lives in that area.

An indicator of the socio-economic characteristic of population can be the number of citizen that can access to the healthcare services without paying in order to improve the accessibility to the healthcare system and assure cares to all citizens; the distribution of the number of citizens with the socio-economic exemption is represented in Figure 5.

**Figure 5** Population with socio-economic exemption (number of persons) (see online version for colours)

From the maps it is possible to see that, in the peripheral zone, the socio-economic conditions of the population are so that the number of habitants with the socio economic exemption is 80 in the central area and 115 in the area on the right.

The analysis on the use of levels of care was conducted using the global indicators that take into account the number of different access to various services of the healthcare system, the number of days of hospitalisation for admissions combined with the average weight of the DRG (Costa et al. 2008).
The ELA indicator for the hospital recovery (Figure 6) for the evaluation of the use of the hospitalisation is computed by considering the days of hospital recovery $d_H$ pondered with a weight equal to 15 plus a dichotomous variable $I_S$, equal to 1 if the patient receives a surgical intervention, 0 otherwise, pondered with a weight equal to 10.

$$ELA_H = 15 \times d_H + 10 \times I_S$$

**Figure 6**  Distribution of number of hospital admissions (see online version for colours)

From the map in Figure 6 it is possible to see that the population that lives in the right area of the city has a greater utilisation of hospital admissions. Each colour corresponds to a different range of the value of the indicator, as detailed in the legend.

The ELA indicator for the specialist services is computed by considering the number of access to each kind of service pondered with the weights of Table 3.

$$ELA_S = 1 \times N_F + 4 \times N_E$$

where $N_F$ is the number of specialist visits and $N_E$ is the number of Laboratory exams.

The distribution of the $ELA_S$ index is shown in Figure 7.

**Table 3**  Weights of specialist services

<table>
<thead>
<tr>
<th>Specialist service</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specialist visit</td>
<td>1</td>
</tr>
<tr>
<td>Laboratory exams</td>
<td>4</td>
</tr>
</tbody>
</table>

From Figure 7 it is possible to notice that the area of the city on the left has the greater numbers of accesses to the specialist services provided by the ambulatories. Each colour corresponds to a different range of the value of the indicator, as detailed in the legend. Figure 6 and Figure 7 show how the use of hospital services is complementary to the use
of specialist services. The hospital and specialist interventions belong to two different hierarchical levels of the organisation of the health service, so a complementary behaviour cannot be accepted as the proper functioning of the system.

Figure 7  Distribution of number of accesses to specialist services (see online version for colours)

Chronic diseases are very important to be analysed for at least two reasons: the first is because, usually, chronic patients do not pay the healthcare services and the total cost of services is covered by public resources, the second reason is that chronic patients constantly and periodically use the healthcare services, so the evaluation of the number of chronic patients give information about the demand of healthcare services.

Table 4  Chronic diseases

<table>
<thead>
<tr>
<th>Chronic disease</th>
<th>Percentage</th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypertension</td>
<td>28%</td>
<td>28%</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>18%</td>
<td>46%</td>
</tr>
<tr>
<td>Malignant neoplastic diseases</td>
<td>13%</td>
<td>59%</td>
</tr>
<tr>
<td>Circulatory system diseases</td>
<td>10%</td>
<td>69%</td>
</tr>
<tr>
<td>Hypothyroidism</td>
<td>5%</td>
<td>74%</td>
</tr>
<tr>
<td>Glaucoma</td>
<td>4%</td>
<td>78%</td>
</tr>
<tr>
<td>Asthma</td>
<td>2%</td>
<td>80%</td>
</tr>
</tbody>
</table>

Table 4 provides an estimation of the chronic diseases that affect the 80% of the chronic population.

The KPI that evaluate the incidence of chronic diseases in the area is the chronicity Index. The index is calculated by considering the number of chronic diseases for a single patient, so it is an index computed on an individual level. The distribution of the mean
value of the chronicity index is represented in Figure 8. Each colour corresponds to a different range of the value of the indicator, as detailed in the legend.

**Figure 8** Distribution of chronicity index (see online version for colours)

6 Conclusions

The conceptual analogy between the process maintenance function and the healthcare services supply, in this work, is the starting point to justify and to transfer the analogy on the modelling scheme and the set of KPIs. This result represents an important guide to analyse the healthcare services system and identify the kind of KPI that can give quantitative information about the territorial conditions where the system delivers services. The proposed model enables to give a guided interpretation of KPI values to evaluate the healthcare system in terms of effectiveness (achievement of the goal to improve health) and in terms of performances (do the best with the available resources). In this way the THA’s manager can have at disposal useful information for the decision making process required by the strategic decisions and allocation of resources. The procedure to implement this methodology requires a well collected and organised set of data that allows the analyst to obtain useful information for the managers to evaluate the performance of the healthcare territorial system.

Once that the analyst, together with the manager has defined the set of KPIs to be measured, they can select among the available data, the field and the records necessary to perform the analysis. The correspondence between industrial and healthcare concept and performance indicators can be used as an instrument to select the interested KPIs and to choose the best solution to improve the performances of the system. In the present work the distribution of the KPI on a real THA is provided. The purpose of the graphical
representation of the KPI on a map, representing the analysed area, is to give an immediate key of lecture of results. It is easier, for the THA’s manager to understand and to interpret results if they are graphically represented on a map that can suggest way of intervention. Figures 4 and 5 provide an estimation of the demand of healthcare services: the average age and the socio-economic conditions are two determinants of the health status, so their values are strictly related to the need of healthcare interventions. Figure 7 and Figure 8 give an indication of the kind of healthcare services supplied in the analysed area. The services that are defined as essential from the WHO are considered. A critical lecture of the result can suggest that the use of the healthcare services is not properly correct in the analysed area and strategic interventions must be done from the THA’s manager. By considering an evolution of the proposed KPI on chronic diseases and monitoring the health status of the population on different and consecutive time period, it is possible to have dynamic trends of evolution in order to predict the consequences of the adopted politic and change if necessary.

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