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A Mathematical Model to Plan the Adoption of EHR Systems

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INTRODUCTION

A systemic diffusion and deployment of eHealth systems and services is occurring worldwide, as it is meant to positively impact and strengthen healthcare professionals daily work, making easier the path of integration and coordination among the different tasks, as well as the deployment of new organizational dynamics. The present chapter is intended to introduce a prescriptive mathematical model to plan the adoption process of an EHR framework, that integrates clinical and administrative information provided by different healthcare operators during the entire citizen's life. In particular, the model establishes how different subjects (GPs and patients) are involved in the testing process and how the resources provided can be invested to find out the most suitable intervention strategies. In this perspective, the objective is twofold: on the one hand, to figure out, besides the intrinsic technical reliability, the EHR proper nature of innovation; on the other hand, to design a realistic, scalable and exportable model, capable of addressing a wide range of clinical, administrative, and financial decisions in healthcare, for a particular kind of patients.

The chapter introduces the mathematical formulation of this model, making clear how and why it can be considered an efficient way to measure "ex-ante" both adequacy and significance of the adoption process.

BACKGROUND

National healthcare systems are called to face considerable challenges, mainly due to fundamental demographic changes, decreasing financial budgets for healthcare and innovative technological developments (Schlessinger & Eddy, 2002; Arning & Ziefle, 2009). Particularly, a systemic diffusion and deployment of eHealth systems and services are then occurring, since those are expected to cover the interaction between patients and health-service providers, institution-to-institution transmission of data as well as peer-to-peer communication between patients or health professionals. Furthermore, the development of high-quality information systems is having a major impact in the delivery of patient services improving the procedures implemented for storing, organizing and sharing clinical data, knowledge and information among healthcare operators. Moreover, information systems foster a stronger connection between hospital and territory, through the development of new skills as well as the diffusion of new technologies (Djellal & Gallouj, 2005).

The successful application and the consequent systematic adoption of Health Information Technologies is broadly considered a promising strategy to improve the economic sustainability of healthcare, while ensuring and enhancing the quality of services (Serbanati, Ricci, Mercurio & Vasileanu, 2011).

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MAIN FOCUS

Issues, Controversies, Problems

EHRs stand worldwide at the heart of many complex platforms for healthcare delivery system, as they can provide each individual with aggregate, secure and private lifetime record of their key health history and care within the health system, and share encounter information available electronically with authorized health care providers and the individual anywhere, anytime in support of high quality care (e.g. Canada Health Infoway, 2006; Ludwick & Doucette, 2009). EHRs and EHR networks are called to be: (i) *longitudinal* (containing records over an extended period of time); (ii) *comprehensive* (containing virtually all clinical encounters with a wide range of healthcare providers); (iii) *interoperable* (accessible in standard electronic format via various EHR systems from any location) (Rothstein, 2010): this makes them heavily involved in managing and monitoring national roadmaps to innovate the eHealth sector (Tang, 2003; eHealth ERA Project, 2007). Their uprising degree of adoption both in public and private sectors of healthcare can lead to lower cost service delivery while increasing the quality of healthcare. It is therefore up to the regional and national competencies to lead and sustain the necessary EHR adoption strategies, along with the costs/investments policies.

In the field of Operational Research, this translates into a series of optimization problems to be worked out, in order to achieve an optimal (or at least the best fitting) allocation of resources, subject to a budget constraint (Stinnett & Paltiel, 1996). Models for the economic evaluation of health technologies can provide – mostly on a national level – valuable information to decision makers, provided that viable and appropriate assumptions are made available from the analysis of the evaluation context (Eldabi, Irani & Paul, 2002; Brennan, Chick & Davies, 2006). Specifically, the use of mathematical modeling is often required for the CEA (Cost–Effectiveness Analysis) issues and decision rules, since CEA

deals with the maximization of aggregate health effectiveness (Johannesson & Weinstein, 1993). On a regional level, the Governments are always called to “match” somehow the national directives with the local issues, and the mentioned budget constraints often make decision makers unable to fund and implement all the healthcare technologies adoption programs with positive net benefits. The relevance of the benefits evaluation becomes so clear, especially given that it strictly depends on the kind of results pursued. This being the case, the challenge turns then in an optimization problem in which benefits have to be maximized subject to a budget constraint, and can be better worked out by using the CBA (Cost–Benefit Analysis) method (Stinnett & Paltiel, 1996). Based on CBA, the model introduced is therefore meant to determine and demonstrate the suitability of the resources provided in order to: (i) address all the issues concerning the feasibility of the adoption process, along with its technical, political and organizational features; (ii) redesign if necessary an adoption and running plan better aligned with the nurtured expectations.

CBA can give a valid support to pursue the “innovation of value” recognizing the benefits coming with the adoption and diffusion of EHR systems in terms of clinical appropriateness, or as support to the treatment of chronic illnesses: a fundamental change of attitude, i.e. centered on healthcare strategies and care processes, with the design of the suitable technological solutions as a consequence (Rossi Mori, 2007).

LUMIR System: A Case Study

The LUMIR system was developed under the direction of the Institute of Biomedical Technologies of the Italian National Research Council (ITB – CNR) (Contenti, Mercurio, Ricci & Serbanati, 2010). It is composed by a “registry” of data and a “repository” of documents supplied by different healthcare providers via an universal wrapper that guarantees the delivery of documents from different Health Care Organizations (HCOs) to LUMIR, and provides the link between LUMIR

and the national EHR superstructure under development. Moreover, LUMIR provides a Web system to access healthcare data and documents of citizens according to privacy regulations. The LUMIR infrastructure of network-enabled services aims at integrating different ICT solutions used by the operators of the Regional Healthcare System, in order to:

- Allow the healthcare professionals of territorial assistance (GPs, lab analysts, nurses, pharmacists, social workers, etc.) to exchange electronically clinical and administrative information concerning the single patient;
- Interconnect the information sub-systems belonging to the single HCOs through timely protocols of data sharing and accesses control;
- Support and improve the integrated management of care and the realization of local to regional policies of healthcare assistance.

The general adoption process was organized in a series of sequential steps, related with the issues to deal with:

1. Prearranging of the process, by exploiting activities for e.g. dealing with privacy issues, getting started with the support services (help-desk), completing the automation of HCOs, etc.;
2. First running of both the LUMIR system and the adoption support services;
3. Expanding the implementation to the HCOs of the Regional Healthcare Systems;
4. Expanding the implementation to private healthcare facilities of the Region, covered or not by insurance.

The adoption process is considered as the longest and the most expensive activity in the software development lifecycle (Smith, 1999); this is particularly true in the healthcare settings, where it is directly related with the successful

system deployment, and particularly deals with the choice of the target pathology and the recognition of the healthcare professionals to enlist in the adoption program (Mantzana, Themistocleous, Irani & Morabito, 2007). The evaluation of the capability for EHR systems to provide timely healthcare services makes it necessary to carefully size a number of strictly connected context variables. The deployment of a mathematical model emerges therefore as a strong and appropriate quantitative approach, in order to design and plan the best possible roadmap. All the professionals involved in the initiative have been asked not only to participate as users, but also to take part as active subjects to the adoption process of the LUMIR system, to address all those issues connected not only to the design features, but also to the EHR diffusion and acceptance, since the project opens toward the development of new ways of healthcare services provision.

To this purpose, in the first place the Regional government focused the attention on chronic-degenerative pathologies and in particular the Diabetes Mellitus type 2, considering its increasing incidence in Italy (Bonacci & Tamburis, 2010).

Model Formulation and Definitions

The mathematical model features the following characteristics:

- It is an additive model, since it features two distinct groups of subjects (GPs and diabetic patients) whose evolution dynamics do not affect each other;
- The chain of events is affected by saturation phenomena, that alter the time dynamics of the model;
- Costs and benefits are directly related to the time trend, according to a process of resources discretization.

The scope of the model is to lead the enlistment plan of the subjects involved in the adoption process of the system; it also aims at verifying both adequacy and significance of the process itself,

with relation to the set of resources allocated by Regional Authorities to adopt the system. To find out the most suitable intervention strategies and the optimal courses of action, a core set of variables was defined, as showed in Table 1.

Such variables have been used to design specific functions to assess the total number of GPs and patients enlisted during the whole process, according to a specific set of parameters. The model has been designed based on two nested iterative adoption processes: GPs (outer process) and patients (inner process). The interaction between these processes can be summarized as follow:

$\forall i \in N^+ \mid i \leq n$, a set of GPs M_i are enrolled in the adoption process,

$\forall m \in M_i$, a set of patients (p_i^m) are enrolled in the adoption process.

In order to facilitate the adoption of an EHR system (in terms of help-desks initialization and data upload, and vocational training for the operators involved), during the first month (start-up phase) only a reduced number of GPs (m_0) is asked to participate; starting from the second

month (running phase), a higher number of users ($m_1 > m_0$) is instead involved.

Based on this assumption, the total number of GPs enlisted in a specific month of the process is summarized in (1).

$$Med(n) = m_0 + m_1 \cdot (n - 1) \quad (1)$$

Similarly, patients enrollment takes into account the mentioned start-up and running dynamics, also including tasks to be carried out by different professionals involved, i.e. GPs, engineers, developers, technicians, etc. In particular:

1. p_0 identifies the number of patients that each m_0 GP is asked to enroll during the first month;
2. $p_1 > p_0$ identifies the number of patients enrolled by: (i) each m_0 GP during its second month; (ii) each m_1 GP during its first month.
3. $p_2 >> p_1$ identifies the number of patients enrolled by each GP during the following months, when the process is fully warmed-up; for this reason, p_2 is assumed to be far greater than p_1 .

Table 1. Core variables of the model

n	Length of the adoption plan (expressed in months)
m_i	Number of GPs to be enlisted in each month ($i = \{1 \dots n\}$) of the adoption process
$Med(n)$	Total number of GPs enlisted in a specific month of the adoption process. $Med(n) = \sum_{i=1}^n m_i$
p_i	Number of patients to be enlisted by each GP in a specific month of the adoption process
Paz_{GP}	Total number of patients enlisted by a GP during the adoption process, depending on the month when the GP is engaged (n_{ing}) $Paz_{GP}(n) = \sum_{i=n_{ing}}^n p_i$
Paz	Total number of patients enlisted in the whole adoption process by all GPs $Paz(n) = \sum_{i=1}^n m_i \cdot \sum_{j=n_{ing}}^n p_j$

Formula (2a) models the number of patients enrolled in a specific month by the m_0 GPs and (2b) shows the number of patients enrolled by the m_1 GPs, taking into account the month when the relevant GP has been engaged (n_{ing}):

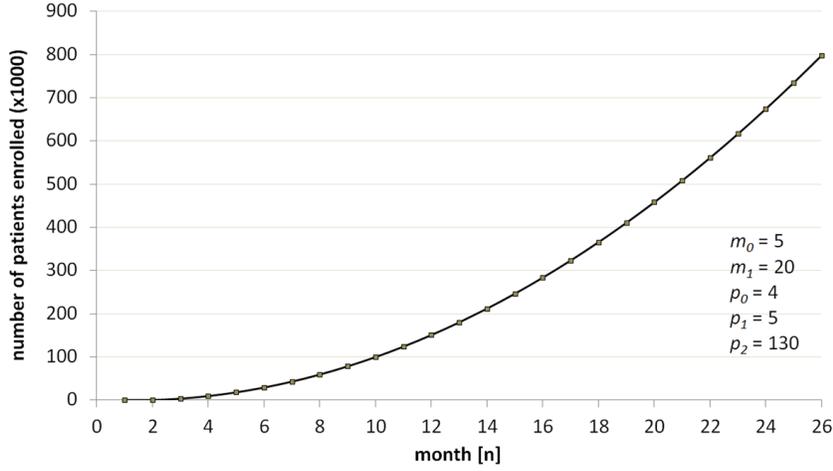
$$Paz_{GP}^{m_0}(n) = p_0 + p_1 + p_2 \cdot (n - 2) \quad (2a)$$

$$Paz_{GP}^{m_1}(n) = p_1 + p_2 \cdot (n - n_{ing}) \quad (2b)$$

Based on (2a-b), the total number of patients enrolled in a specific month (n) of the process is reported in (3a-b) and the relevant trend is depicted in Figure 1.

$$Paz(n = 1) = m_0 \cdot p_0 \quad (3a)$$

Figure 1. Trend of the patients enrollment per month in the whole testing process



$$\begin{aligned}
 Paz(n > 1) &= m_0 \cdot Paz_{GP}^{m_0}(n) + m_1 \cdot \\
 &\cdot \sum_{n_{ing}=2}^n Paz_{GP}^{m_1}(n) = m_0 \cdot [p_0 + p_1 + p_2 \cdot (n-2)] + \\
 &+ m_1 \cdot \sum_{n_{ing}=2}^n [p_1 + p_2 \cdot (n - n_{ing})] = \\
 &= m_0 \cdot [p_0 + p_1 + p_2 \cdot (n-2)] + \\
 &+ m_1 \cdot \left\{ p_1 \cdot (n-1) + p_2 \cdot \left[\frac{(n-1) \cdot (n-2)}{2} \right] \right\}
 \end{aligned} \tag{3b}$$

Constraints

Given the “political” nature of the healthcare setting considered, the further step was to define the “admissibility field,” in which to work out the best “objective function”. A set of constraints was therefore set up considering different aspects such as help–desk dimension, number of admissible subjects, length of experimentation, human and instrumental resources availability, time scheduling constraints, estimation of the social–organizational outcomes, as well as costs sustainability. The list of constrained variables is summarized in Table 2; for each variable, the description and the ground of the relevant constraint, as well as the function affected, are considered.

Starting from these constraints, the mentioned saturation phenomena are detected; in particular,

three saturation points can be observed when: (i) total number of GPs (n_{med} , see 4a), (ii) total patients per GP (n_{sat} , see 4b) and (iii) total number of patients (n_{last} , see 4c) are enrolled.

- **GP Saturation:**

$$n_{med} = \left\lfloor \frac{M_{med} - m_0}{m_1} \right\rfloor \tag{4a}$$

where $\lfloor x \rfloor$ hereafter symbolizes the largest integer not greater than x .

- **Patients per GP Saturation:**

$$\begin{cases} n_{sat} = n_{sat}^{m_0} = \left\lfloor \frac{P_{real} - p_0 - p_1}{p_2} \right\rfloor + 3 \\ n_{sat}^{m_1} = \frac{P_{real} - p_1}{p_2} + n_{ing} + 1 \end{cases} \tag{4b}$$

Note that, for $n_{ing}=2$ (i.e. the month when the first group of m_1 GPs is enrolled), $n_{sat}^{m_1} \equiv n_{sat}^{m_0}$, given that $p_0/p_2 \ll 1$. Clearly, GPs and patients per GP saturation points are mathematically independent from each other; moreover, the time sequence of the saturations largely depends on the maximum number of GPs (M_{med}) and patients

Table 2. Constraints of the model

Variable	Description of Constraint	Constraint
M_{med}	Maximum number of GPs that can be enrolled during the whole process. It is assumed not to exceed the 50% of the total number of GPs over the relevant territory.	$m_0 + m_1 \cdot (n - 1) \leq M_{med}$
P_{sup}	Maximum number of patients that can be enrolled each month by a single GP. As introduced, the number of patients enrolled during the first month (p_0 for the m_0 GPs; p_1 for the m_1 GPs) are markedly lower than the (p_2) enrolled afterward.	$p_0 < p_1 \ll p_2 \leq P_{sup}$
P_{real}	Maximum number of patients that a single GP can enroll during the whole adoption process. The value is assumed not to exceed the 50% of the average number of patients of each GP.	$p_0 + p_1 + p_2 \cdot (n - 2) \leq P_{real}$ $p_1 + p_2 \cdot (n - n_{ing}) \leq P_{real}$
$n_{inf}, n_{sup}, n_{last}$	Minimum (n_{inf}) and maximum (n_{sup}) number of months for the running period of the process. Note that, for the purpose of this analysis, the process can finish only when all GPs and all patients are enrolled (n_{last}).	$n_{inf} < n \leq n_{sup} \leq n_{last}$

per GP (P_{real}) to be enrolled; it also depends on the enrolment dynamics ruled by the number of GPs and patients per GP enrolled each month (respectively, m_1 and p_2).

On the contrary, population saturation strictly depends on patient per GP saturation of the last set of GPs enrolled:

$$n_{last} = n_{sat}^{m_1, last} = n_{sat}^{m_1} \Big|_{n_{ing} - n_{med}} = \frac{P_{real} - P_1}{P_2} + n_{med} + 1 \quad (4c)$$

In accordance with these constraints, (1) and (2a-b) are updated into (5) and (6a-b) and showed in Figure 2. As highlighted in the graph, based on these values GP saturation (4a, $n_{med} = 6$) precedes patients per GP saturation (4b, $n_{sat}^{m_0} = 9$). Moreover, population saturation occurs during the 13th month (4c, $n_{last} = 13$), as displayed in Figure 3.

$$Med(n) = \begin{cases} m_0 + m_1 \cdot (n - 1) \\ M_{med} \end{cases} \quad (5)$$

$$\forall n \mid 0 < n < n_{med}$$

$$\forall n \mid n \geq n_{med}$$

Figure 2. Trend of the GPs and patients per GP involvement in the whole testing process

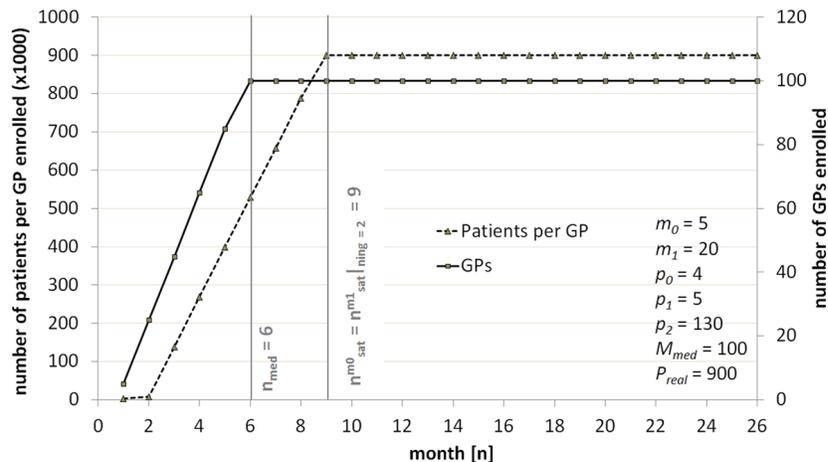
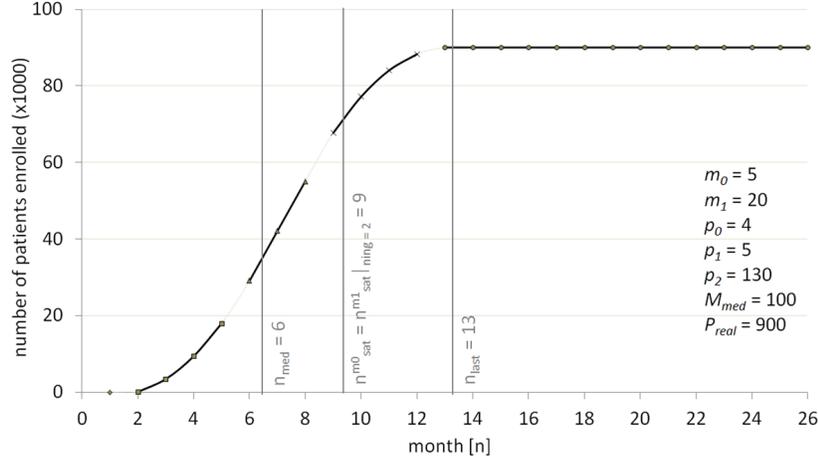


Figure 3. Trend of patients per month enrolment in the whole testing process considering the mathematical model constraints



$$Paz_{GP}^{m_0} = \begin{cases} p_1 + p_2 \cdot (n - n_{ing}) \\ P_{real} \end{cases} \quad (6a)$$

$$\forall n \mid 0 < n < n_{sat}^{m_0}$$

$$\forall n \mid n \geq n_{sat}^{m_0}$$

$$Paz_{GP}^{m_1}(n) = \begin{cases} p_1 + p_2 \cdot (n - n_{ing}) \\ P_{real} \end{cases} \quad (6b)$$

$$\forall n \mid 0 < n < n_{sat}^{m_1}$$

$$\forall n \mid n \geq n_{sat}^{m_1}$$

Starting from (5) and (6a-b) we can also compute the number of GPs enrolled at n_{med} (6c), as well as the number of patients enrolled by m_0 and m_1 at n_{sat} (6d-e):

$$m_x = M_{med} - \left[m_0 + m_1 \cdot (n_{med} - 2) \right] \quad (6c)$$

$$Paz_x^{m_0} = P_{real} - \left[p_0 + p_1 + p_2 \cdot (n_{sat}^{m_0} - 2) \right] \quad (6d)$$

$$Paz_x^{m_1} = P_{real} - \left[p_1 + p_2 \cdot (n_{sat}^{m_1} - 2) \right] \quad (6e)$$

Saturation phenomena introduce a set of points of removable discontinuity in the adoption process timeline. Formulas (1-6) are now used to compute the total number of patients enrolled during the whole process, as reported in (7a-f) and showed in Figure 3.

$$Paz(n=1) = m_0 \cdot p_0 \quad (7a)$$

$$\begin{aligned} Paz(n < n_{sat} \wedge n < n_{med}) &= \\ &= m_0 \cdot \left[p_0 + p_1 + p_2 \cdot (n - 2) \right] + \\ &+ m_1 \cdot \sum_{n_{ing}=2}^n \left[p_1 + p_2 \cdot (n - n_{ing}) \right] \end{aligned} \quad (7b)$$

$$\begin{aligned} Paz(n \geq n_{med} \wedge n < n_{sat}) &= \\ &= m_0 \cdot \left[p_0 + p_1 + p_2 \cdot (n_{med} - 2) \right] + \\ &+ m_1 \cdot \sum_{n_{ing}=2}^n \left[p_1 + p_2 \cdot (n_{med} - n_{ing}) \right] + \\ &+ p_1 \cdot m_x + p_2 \cdot M_{med} \cdot (n - n_{med}) \end{aligned} \quad (7c)$$

$$\begin{aligned}
 Paz(n \geq n_{med} \wedge n \geq n_{sat}^{m_0}) &= \\
 &= \left[m_0 + m_1 \cdot (n - n_{sat} + 1) \right] \cdot P_{real} + m_1 \cdot \\
 &\cdot \sum_{n_{ing}=2}^{n_{sat}-1} \left[p_1 + p_2 \cdot (n_{sat} - n_{ing} + 1) \right]
 \end{aligned} \quad (7d)$$

$$\begin{aligned}
 Paz(n \geq n_{med} \wedge n \geq n_{sat} \wedge n < n_{last}) &= \\
 &= \left[m_0 + m_1 \cdot (n - n_{sat} + 1) \right] \cdot P_{real} + m_1 \cdot \\
 &\cdot \sum_{n_{ing}=2}^{n_{med}-1} \left[p_1 + p_2 \cdot (n - n_{ing}) \right] + m_x \cdot \\
 &\cdot \left[p_1 + p_2 \cdot (n - n_{med}) \right]
 \end{aligned} \quad (7e)$$

$$Paz(n \geq n_{last}) = P_{real} \cdot M_{med} \quad (7f)$$

Objective Function

In the healthcare settings, as in many others disciplines, two main targets of an intervention are usually considered: (i) minimize the investments to be spent to run the information system during the adoption process; (ii) maximize the benefits coming from the use of the system. In our approach, both targets have been considered to determine the objective function of the model.

Costs refer to the management of the information system and to support the users involved including:

1. Management of the help-desk, through which GPs can receive help in using the software, or get answers about software issues, via free dial number, website or e-mail (c_{hd}^{tot});
2. Installation and management of the software components on GPs' computers (c_w^{tot});
3. Management and deployment of specific training courses for GPs to appropriately deploy the information system (c_t^{tot}). Costs function is summarized as follow:

$$Costs(n) = c_{hd}^{tot} + c_w^{tot} + c_t^{tot} \quad (8a)$$

A

The first term is proportional to the length of the whole testing process (n) and to the fixed cost per month to be spent to manage the help-desk (c_{hd}).

$$c_{hd}^{tot} = n \cdot c_{hd} \quad (8b)$$

The second term depends on: (i) duration of the GPs enrolment phase (n_{med}); (ii) price per month to be paid to each technician in charge for the installation of the wrapper in the GP's computer (c_w); (iii) number of technicians requested to assist the GPs enrolled each month ($[Med(i) - Med(i-1)]$); (iv) number of wrappers per month installed by each technician (w). Provided that (5) describes the GP enrolment activity, the related costs function should be modeled as follows:

$$\begin{aligned}
 c_w^{tot}(n \geq n_{med}) &= c_w \cdot \\
 &\cdot \sum_{i=1}^{n_{med}} \left\{ \left[\frac{[Med(i) - Med(i-1)] - 1}{w} + 1 \right] \right\} = \\
 &\left[\left[\frac{m_0 - 1}{w} + 1 \right] \right. \\
 &\left. + \left[\frac{m_1 - 1}{w} + 1 \right] \cdot (n_{med} - 2) \right\} \\
 &\left[\frac{m_x - 1}{w} + 1 \right]
 \end{aligned} \quad (8c)$$

where $Med(0) = 0$.

The third term depends on: (i) duration of the GPs enrolment phase (n_{med}); (ii) price per month to be spent for each training lesson (c_t); (iii) number of lessons needed to train the GPs enrolled each month; (iv) number of delegates that can attend each lesson (d). Using (5) to model GP enrolment activity, this term can be modeled as follows:

$$\begin{aligned}
 c_t^{tot} (n \geq n_{med}) &= c_t \cdot \\
 &\cdot \sum_{i=1}^{n_{med}} \left\{ \left[\frac{[Med(i) - (med(i-1)) - 1]}{d} \right] + 1 \right\} = \\
 &= c_t \cdot \left[\left[\left(\frac{m_0 - 1}{d} \right) + 1 \right] \right. \\
 &\quad \left. + \left[\left(\frac{m_1 - 1}{d} \right) + 1 \right] \right] \cdot (n_{med} - 2) \\
 &\quad + \left[\left(\frac{m_x - 1}{d} \right) + 1 \right] \quad (8d)
 \end{aligned}$$

Costs analysis introduces another constraint for the model, related to the limited budget that can be invested to implement an EHR system. The constraints enlisted in Table 2, are therefore integrated as follows:

$$c_{hd}^{tot} + c_w^{tot} + c_t^{tot} \leq B_{tot} \quad (9)$$

where B_{tot} means the maximum amount of money that can be invested to test the information system. The total costs estimated to implement the adoption process often comprise the economic incentives provided by national or regional authorities to encourage the adoption and diffusion of information technologies. However, in the proposed analysis these costs are not considered in the total budget provided, since they feature as a constant value that is independent from the variables included in the mathematical model.

The appropriate usage of Health Information Technologies occurs as an important opportunity to reduce clinical errors, to support healthcare professionals, to increase the efficiency of care, or even to improve the quality of patient care. These strategic advantages are among the most important *benefits* coming with the use of EHRs, by means of an ubiquitous and secure electronic exchange of clinical data among different stakeholders and environments (i.e. hospitals, ambulatory, laboratory, etc.). Our hypothesis is that for EHR systems such benefits can be modeled by measuring the

number of encounters between each GP and his/her patients during the whole adoption process.

Thus, benefits depend on: (i) number of patients enrolled per month; (ii) number of month in which the patient is involved ($n - n_{ing}$); (iii) number of expected months between two following encounters of the same patient (\bar{t}); specifically, the latter was identified by analyzing regional and national guidelines (e.g. A.M.D. & S.I.D., 2011), along with the trends occurred for the involved GPs.

$$\begin{aligned}
 Benefits(n) &= \\
 &= \left\{ \sum_{n_{ing}=1}^n \left[\left(Paz(n_{ing}) - Paz(n_{ing} - 1) \right) \cdot \left[\left(\frac{n - n_{ing}}{\bar{t}} \right) + 1 \right] \right] \right\} \quad (10)
 \end{aligned}$$

where $Paz(0) = 0$.

Based on CBA, the objective function can be determined as the ratio between benefits and costs: the main goal is to maximize the number of encounters subject to a budget constraint.

$$\begin{aligned}
 \text{o.f.} &= \max (f(n)) = \\
 &= \max \left\{ \frac{Benefits(n)}{Cost(n)} \right\} \quad (11)
 \end{aligned}$$

Data Setting and Mathematical Model Workflow

After working out the main rules to set up of the adoption process, the next step of the study was to figure out what parameters of the mathematical model to consider either as a variable, or as a constant. This was possible by means of the analysis of the resources made available from the Basilicata Region to run the LUMIR project.

Table 3 summarizes both initial values for the constants, and range values for the variables.

The mathematical model has been solved deploying a software component properly customized for this purpose, and developed in MATLAB® computing environment.

To determine the optimal point $P^{opt} (n^{opt}, m_1^{opt}, p_2^{opt})$ a branch-and-bound algo-



Table 3. Constants and variable values of the mathematical model

Name	Value	Criteria
Constants		
m_0	5	The low values of these variables allow a better start-up for the testing phase. Moreover, they do not affect the performance of the mathematical model
p_0	4	
p_1	5	
M_{med}	100	$M_{med} \approx 45\%$ of the total GPs of Basilicata Region; $P_{real} \approx 21\%$ of total inhabitants of Basilicata Region
P_{real}	900	
c_{hd}	3.000	Values are expressed in Euros
c_w	1.500	
c_t	1.500	
B_{tot}	80.000	
\bar{t}	6	This value has been assessed considering the Basilicata population and the relevant incidence of diabetes patients, as well as the average number of months between two consecutive encounters GP/patient
Variables		
n	$n_{last} \geq n \geq n_{sup}$ $n_{sup} = 26$	Considering the budget available (B_{tot}) and the costs per month for the help-desk management (c_{hd}), the maximum length of the adoption process cannot exceed 26 months, as defined in (8b): $n_{sup} = \lfloor B_{tot} / c_{hd} \rfloor$
m_j	$10 \leq m_j \leq 40$	Lower and upper bound of these variables have been set along with the Regional stakeholders, depending on the enrolment dynamics foreseen.
p_2	$80 \leq p_2 \leq 130$	

rithm was used; it consists in a systematic evaluation of the objective function (f) for all candidate points (P) considering the following steps:

1. For each possible couple $p^i \{m_j^i, p_2^i\}$;
 - a. Saturation points n_{med}^i, n_{sat}^i and n_{last}^i , are computed;
 - b. Lower bound of n is determined based on the population saturation point ($n_{inf} = n_{last}^i$)
 - c. Upper bound of n is determined based on: the budget to be allocated for the help desk management (see 9) and the GP saturation point (n_{med}^i):

$$n_{sup} = \frac{(B_{tot} - c_w^{tot} - c_t^{tot})}{c_{hd}} \quad (13)$$

- d. For each $n_j \mid n_{sup} \geq n_j \geq n_{inf}$ relevant costs (formulas 8a-d) are computed:
 - i. If costs do not exceed the budget, benefits and relevant ratio are computed (formulas 10 and 11), so that $f(P_j^i) = f(n_j, m_j^i, p_2^i)$ is considered as an eligible optimal point;
 - ii. If costs exceed the budget, result of this calculation is discarded and no further computation is performed;
- e. The optimal point is then determined based on (12) and taking into account eligible points computed at the step (i).

Results

The main results obtained are summarized as follows in Table 4.

Table 4. Results of the mathematical model

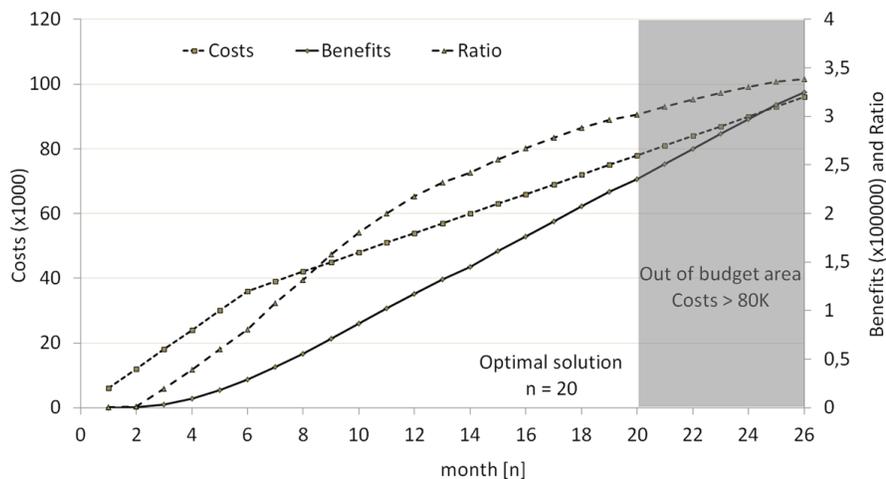
Name	Optimal Value	Variable Description
Optimal point		
n	20 months	Total number of months of the adoption process
m_j	20 GPs	GPs involved per months, starting from the second month
p_2	130 patients	Patients enrolled per month per GP, starting from the second month
Saturation points		
n_{med}	6 months	GPs saturation
n_{sat}	9 months	Patients per GP start to saturate
n_{last}	13 months	Population saturation
Optimal solution		
Costs	78.000 Euros	Total costs considering that $B_{tot} = 80.000$ Euros
Benefits	235.265 encounters	Total number of encounters between patients and GPs
Ratio	3,02	Number of encounters carried out for each Euro invested in the adoption process.

The trend of costs, benefits and relevant ratio in the whole adoption process are showed in Figure 4, along with the optimal solution achieved.

The optimal value of p_2 is the maximum of the range considered. This result is due to the following considerations: (i) the quicker is the saturation for the patients per GP, the more encounters can be carried out during the following months of the process, thus affecting the benefits value of the proposed solution; (ii) costs are not affected by this variable.

The optimal value of m_j is related to: (i) the available budget that can be allocated in the whole adoption process; (ii) the number of technician to be involved for wrappers installation, as well as the number of lessons per month to carry out for professionals' training courses. The optimal value of n is mainly related to the availability of the budget that can be allocated in the whole adoption process. In fact, should an extra budget be provided (for instance, $B_{tot} = 81.000$ Euros would allow the adoption process to run for one more month), the number of encounters would

Figure 4. Trend of costs, benefits and relevant ratio over the whole adoption process



increase of 7%, whereas costs would increase of 4%. This trend is confirmed for any additional budget provided, as made evident in Figure 4, where the objective function is a monotonically increasing function.

In order to analyze how the optimal solution (both optimal point and cost benefit ratio) varies with respect to the changes on the resources deployed, a preliminary sensitivity analysis has been performed taking into account the coefficients of the constraint functions (M_{max} , P_{real}) and the budget to be invested (B_{tot}). Considering the GPs involved during the whole process (M_{max}), there are no significant differences as for the optimal solution point and the relevant ratio when M_{max} is lower than 100 units. Conversely, involving a higher number of GPs affects the optimal solution ($n = 19$, $m_1 = 30$, $p_2 = 130$) and the ratio increases up to 14% for $M_{max} = 120$, mainly due to the increasing number of encounters (16% more than in the optimal solution).

Analyzing the number of patients enrolled by each GP (P_{real}), for each 10 patients added to/taken from the reference value ($P_{real} = 900$), it was found that the number of encounters and the ratio increases/decreases about 1%. On the contrary, as stated before there are no changes in the total costs since they are not affected by the number of patients enrolled. Considering the budget invested (B_{tot}) and starting from the reference value (80K Euros) the ratio decreases up to 0,4% for each 1000 Euros taken from the budget, whereas it increases up to 1% for each 1000 Euros added to the budget. The maximum budget permitted is 96K Euros, with the optimal point in ($n = 26$, $m_1 = 20$ e $p_2 = 130$). Finally, even if \bar{t} strictly depends on patients' pathology taken into account, there is a remarkable increasing value of the benefits as well as of the ratio if each GP-patient encounter takes place every two months (115%) or every 4 months (29%). On the contrary, this variable does not influence costs.

DISCUSSION

Many debates across the last and the present century have focused on the decision about which model should be chosen in a particular health economic evaluation context. This becomes particularly difficult when the model deals with Public Health-related dynamics (e.g. McKendrick, 1926; Elveback & Varma, 1965; Brennan, Chick & Davies, 2006; Star & Moghadas, 2010). Modeling generally relies on a set of formulas based on assumptions about the accuracy of screening methods, rates of disease progression to end-stage complications or death with and without a particular treatment, and treatment costs. In chronic diseases, empirical studies of interventions, for which outcomes will not be evident for many years, are seldom performed because of high costs and time delays. The relatively inexpensive and rapid results generated by modeling studies are highly influenced by assumptions and represent predictions rather than observations. Nonetheless, such studies have supplied most of the existing data about the economic impact of interventions for diabetes (e.g. Gray et al., 2000; Klonoff & Schwartz, 2000).

In our case study, one of the main activities to validate and verify the LUMIR system was the software adoption process, performed by a limited audience of target users (diabetic patients) in order to: (i) get a feedback of the system functionality (i.e. performance, usability, etc.) in a professional daily work; (ii) check up on its efficacy as high quality and safety healthcare software (Luzi & Pecoraro, 2012). The model proposed in this chapter is built by means of a business process: it is therefore a conceptual model, based on experiences in software dissemination for healthcare operators and aimed at verifying technically the quality of decisions taken to find a solution as intersection between political and managerial needs. Moreover, the model aims at prescribing an optimal allocation of resources for a decision

maker constrained by a fixed budget, where state changes have been designed as deterministic: we had in fact an *a priori* knowledge of the set of parameters (variables and constants) available, and lower and upper bounds for m_1 and p_2 (as well as the choice of the kind of patients to involve) were determined from the beginning along with the Regional stakeholders. This made us capable of precisely foresee and control the model running dynamics.

The present work showed therefore, by means of the CBA method, how the LUMIR initiative is capable to work out a scalable and exportable model of advanced management of clinical information, towards a stronger cooperation among the provider organizations and a better governance of care processes, as crucial element within the more general path of modernization of the healthcare sector.

An important strong point descending from the model setting is its scalability to the set of chronic–degenerative pathologies (since the clinical course is the same as diabetes’, see e.g. Pelella, Tamburis & Bonacci, 2009), as well as of software architecture. It has been found in fact that using a Web–based technology (instead of the universal wrapper) to delivery clinical documents via dedicated software (*add-on*) from the HCOs to the LUMIR mainframe, and then to the national EHR superstructure:

- c_{hd} does not change, since the help–desk still has to be considered, so that the choice of p_0 , m_0 and m_1 remains unaltered;
- c_w^{tot} disappears as is, but it turns into the costs the Region has to pay to provide GPs with the add–ons;
- c_t^{tot} does not change, since the enrolment phase requests the involved GPs to undergo at least one lesson to get used with the system;
- The start-up and the warm-up dynamics are supposed not to change, since they do not depend on the specific software architec-

ture. The sizing and the adoption sequence of both m_i and p_i groups remain therefore unaltered;

- The Benefits remain the same as computed in (10).

FUTURE RESEARCH DIRECTIONS AND CONCLUSION

The implementation of the Cost–Benefit Analysis, in particular to arrange and work out the objective function (rather than aggregate, effectiveness–based methods) made at least possible to show how the LUMIR project is oriented to drive the definition of timely policies of EHR deployment on a regional scale, based on an actual comprehension of the real information needs of the future users of the system. The adoption of any health technology requests in fact to find out in the first place whether or not it: (i) is actually accessible from the ones who need it (*availability*); (ii) can lead to a better health status (*efficacy*); (iii) can be measured through only one “natural” parameter, so to get to an easier assessment between two or more alternatives (*cost–efficacy*); (iv) actually affects patients’ everyday habits (*effectiveness*); (v) comes with sustainable costs (*cost–effectiveness*) (Tamburis, 2009).

For what concerns the LUMIR system: (i) the installation of the wrappers grants the access to the EHR framework for all the professionals involved; (ii) the evaluation of the benefits is closely related to the positive impact of the system on the whole care path of chronic patients; (iii) the overview on the adoption dynamics is based for the greater part on the setting of the most suitable number of m_0 and m_1 groups of GPs involved, with each group designed as a distinct individual; (iv) capturing primary clinical data from healthcare providers in a way that they can be applied to policy decisions for populations can make the Region capable to achieve the goal of providing high-quality, affordable healthcare for all; (v) the budget constraints

have been made clear from the beginning, so that the initiative costs could be properly sized.

In the present chapter we introduced a prescriptive model, that can be validated either through several ex-post performance evaluations of the prescriptions, or using historical events and outcomes (McCarl & Apland, 1986). In particular, the latter approach cannot be applied due to the novelty of the model proposed. At this stage of our research the model has been validated by *construct*, since it has been developed, and model data have been deducted by real world observations. The model has been furthermore defined by means of a participative approach including stakeholders (policy makers, medial associations, ICT analysts, etc.), based on the understanding needs and problems of the adoption process and on the intercommunication between the stakeholders of different areas (Eldabi, Irani & Paul, 2002). For these reasons the model is judged valid, as highlighted by (McCarl & Apland, 1986).

In addition, LUMIR system has actually been exploited in Basilicata Region, and its validation and verification with real users on the basis of the mathematical model has been planned. The information collected during the adoption process will be used to evaluate the performance of the implemented solutions and verify the changes on GPs' work habits, and for an ex-post validation of the mathematical model itself.

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KEY TERMS AND DEFINITIONS

A

Additive Model: A generalized nonparametric linear regression model.

Cost–Benefit Analysis: A systematic process for calculating and comparing benefits and costs of a project, decision or government policy.

Diabetes Mellitus: A group of metabolic diseases in which a person has high blood sugar, either because the pancreas does not produce enough insulin, or because cells do not respond to the insulin that is produced.

e-Healthcare: Healthcare practice supported by Information and Communication Technologies.

Electronic Health Record (EHR): Healthcare record that provides clinician (and increasingly consumer) access to clinical details captured from one or more encounters.

Healthcare Information System: An integrated information system designed to manage the medical, administrative, financial and legal aspects of a hospital and its service processing.

LUMIR: Project that aims to foster collaborative, cross organizational and patient-centric healthcare processes, supporting different stakeholders in the communication of patient clinical information.

Mathematical Modeling: Description of a system using mathematical concepts and language.