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NATALJA GRISCENKO

Comparison and Evaluation of the Telehealth Systems Using a Discrete Event Simulation

Supervisors: Prof Ashutosh Tiwari and Dr Jeffrey Alcock

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Abstract

The telehealth is the delivery of health-related services at a distance using communication technologies. The telehealth provides important benefits: allows to provide the access to the healthcare service reducing need for a physical stay and decreasing the healthcare cost. This industry's popularity and the importance constantly increases because of the number of rapid increase of the population share affected by the chronic diseases.

However, the telehealth service development requires substantial investment of finances, time and substantial expertise. A method of comparison and evaluation of the current telehealth systems helps to create the telehealth service while minimising an amount of the resources wasted.

The method to simulate, evaluate, and compare the telehealth systems have been created through the review of the state-of-the-art techniques of evaluation and comparison of the existing telehealth systems. Then, it was applied to several the real life telehealth systems.

The outcome of this work is (i) the method to construct Discrete Event Simulation (DES) models of the telehealth systems, (ii) twelve the DES models of the current telehealth systems, (iii) the list of suggestions for the future research to increase the quality of the DES models, (iv) the method to choose parameters and to develop metrics to evaluate the telehealth systems, (v) the method to define an approach to compare the telehealth systems, (vi) the evaluation and comparison results of twelve the current telehealth systems.

The bottom line of the current research is that the simulation is an effective way to evaluate and compare the telehealth systems. The DES approach is a viable way of gaining an insight into the telehealth systems properties, although it requires a substantial amount of the future research to mature the method to evaluate and compare the telehealth systems.

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List of Acronyms

ABS	Agent–Based Simulation
BP Monitor	Blood pressure monitor
BP	Blood pressure
CHF	Congestive heart failure
COPD	Chronic obstructive pulmonary disease
CPU	Central Processing Unit
DES	Discrete Event Simulation
ECG monitor	Electrocardiogram monitor
EPR	Electronic Patient Record
FDA	Food and Drug Administration
GPRS	General Packet Radio Services
GP	General Practitioner
HDD	Hard Disk Drive
HTTP	Hypertext Transfer Protocol
I/O	Input/Output
IT	Information Technology
LAN	Local Area Network
MCC	Monitoring Call Centre

MCS	Monte Carlo Simulation
MP	Mobile Phone
NHS	National Health Service
PC	Personal Computer
POC device	Point–of–care device
PSTN	Public Switched Telephone Network
RAM	Random Access Memory
SD	System Dynamics
SMS	Short Messaging Service
SSL	Secure Sockets Layer
TMM	Telehealth Monitor Message
USB	Universal Serial Bus
VSM	Vital Signs Monitor

Chapter 1

Introduction

Medicine developed so well during the 20th century that people have started to live much longer. The number of the elderly people has increased rapidly in the developed countries Koch (2006). However, the elderly people not being very active, have a high probability of getting the chronic diseases or having on-going and prolonged problems with their internal organs. So, the elderly people require a considerable volume of medical care and monitoring. And at the same time, ambient pollution has provoked the speedy growth of chronic diseases Jirtle & Skinner (2007), Mutius (2000), Freudenberg & Olden (2011). Also the consumption of tobacco, alcohol, and eating food with high content of fat, sugar, salt and calories lead to the increase of chronic disease and deaths Freudenberg & Olden (2011). "In developed countries, chronic disease now accounts for more than 75% of health care expenditure and nearly an equivalent percentage of disease–related deaths Celler et al. (1999)." People with chronic conditions also require great medical attention simultaneously for living as active as possible.

As a result of the distribution of diseases and population getting older, the economic requests rapid changes in healthcare service delivery models. The healthcare service delivery models to cope with the new challenges need to pay more attention to the continuity of care, community and home-based care, disease prevention, and multidisciplinary team approach Lovell et al. (2010). To support new priorities of healthcare service delivery, new technology and services process optimisation are required. Information Technology (IT) is actively used in the healthcare service delivery systems building. "The rapid development of information and communication technologies runs parallel to these societal changes and offers the possibilities to cope with the above-mentioned challenges Koch (2006)."

Telehealth is being developed very fast, because it provides three primary benefits American Telemedicine Association (n.d.):

- Improved Access – telehealth delivers healthcare service to patients in distant locations and telehealth essentially extends medical personals' reach, beyond their own offices.

- Cost Efficiencies – telehealth cuts down expenses of healthcare and increases efficiency, because it allows to exclude a need for a health professional and patient to physically stay in one place, and to make more rapid changes in patient's medication.
- Patient Demand – telehealth provides patients the access to healthcare specialists that might not be available otherwise, and reduces the need to travel to long distances.

1.1 Research Goals

1.1.1 Research Aim

The aim of this research is to develop a method to evaluate and compare the telehealth systems.

1.1.2 Research Objectives

To help to achieve the research aim, the following objectives were identified:

1. To review the state-of-the-art in evaluation and comparison of the telehealth systems.
2. To develop a method to simulate, evaluate and compare the telehealth systems.
3. To apply the method to real examples of the telehealth systems.
4. To validate with comparison of current the telehealth systems.

Chapter 2

Literature Review

2.1 Definition of Telehealth Systems

There is no common definition of 'telehealth' in literature. The terms 'telemedicine' and 'telehealth' are often used interchangeably Ekeland et al. (2010), Klecun-Dabrowska (2002), American Telemedicine Association (n.d.). The term 'telemedicine' appeared in 1970s Katharaki (2006) and since then, it has been changed, altered, added, and improved. The reason is information and communications technology's rapid development and healthcare service delivery systems' functional and technical improvement Paul Jen-Hwa Hu (2002), Lovell et al. (2010).

First known definition of telemedicine is offered by Lovett & Bashshur (1979): "Telemedicine is the application of telecommunications technology to the communication and control tasks of health care in consort with an organisational setting, personnel, and manner of conducting care which employs the benefits of telecommunications to transcend barriers of time and space. As a communications system, telemedicine represents a new mode for the production, distribution, and control of medical care data and services. Telemedicine also constitutes an organisational innovation, changing the form and content of the diagnostic process, as well as consultation, supervision, direct patient care, administration and management, and education and training". The publication reviews the role of the telecommunication technology in health care delivery services development and provision. At that time (1979), the communication technology was represented by telephones, radio and television. The aim of the research was to provide an appropriate care to the entire the United States of America.

Another definition of telemedicine can be found in literature Preston et al. (1992): "Telecommunication that connects a patient and a healthcare provider through live two–way audio, two–way video transmission across distances, and that permits effective diagnosis, treatment and other healthcare activities". The publication is written to describe the evaluation of telemedical training and analysis of the telemedical services' cost practicability. Also the publication underlines important function of the telemedicine – communication of healthcare professionals for knowledge sharing and achievement of best possible results for treating of patient.

The definition by Bashshur (1995): "Telemedicine is conceived of here as an integrated and complete system of healthcare delivery and education, that is positioned to exploit the available technological, organisational, and systemic capabilities". The publication's goal is to define a role of the telemedicine in healthcare system, and basic criteria of telemedicine evaluation. The definition implies the context of systems for healthcare services delivery.

Lovell et al. (2010) delivers such definition: "Telemedicine is typically defined as a system of healthcare delivery in which physicians examine patients through the use of telecommunications technologies, that is, remote diagnosis". This publication is the result of Institute of Electrical and Electronics Engineers Engineering in Medicine and Biology Society Annual International Conference, and is focused on describing of the existent systems which help to manage chronic disease. So, this definition is oriented to transferring a data for chronic disease diagnosis and monitoring. Publication describes commercialised systems.

Another literature sources assert that term 'telehealth' is broader then 'telemedicine' Koch (2006), Lovell et al. (2010).

Koch (2006) provides a definition of the term 'telehealth': "the use of audio, video and other telecommunications and electronic information processing technologies for the transmission of information and data relevant to diagnosis and treatment of medical conditions, or to provide health services or aid healthcare personnel at distant sites. 'Telehealth' is often considered to have a broader scope towards health promotion and disease prevention". The object of the publication is to give an outline of the current state of home telehealth research. Sources for this publication are not only the scientific literature but also various non–peer–reviewed magazines, newsletters, books, conference papers, government and other agency or general reports. So definition of 'telehealth' in this publication is full of content, medical data transfer ways and the usage of the medical data.

Publication Lovell et al. (2010) offers a definition of 'telehealth' which is based on definition of 'telemedicine' and broadens it: "Telehealth incorporates a wider range of health-related activities, including patient and provider education, point-of-care diagnostics, clinical decision support services, and most importantly, provides tools for self-management of disease and wellness". The publication is focused on health care delivery systems functions which is especially important for chronic disease diagnosis and management.

In literature source ICUcare LLC (n.d.) was found such describing of relations between terms 'telehealth', 'telemedicine' and 'e–health': "Like the terms 'medicine' and 'health care', telemedicine often refers only to the provision of clinical services while the term ‘telehealth’ can refer to clinical and non-clinical services such as medical education, administration, and research. The term ‘e-health’ is often, particularly in the UK and Europe, used as an umbrella term that includes telehealth, electronic medical records, and other components of health IT”. The publication was produced by a company which develops medical information and communication systems using innovative information and communication technologies. The document’s goal is to introduce the concept of telemedicine.

This definition is used mostly in this thesis because medicine is branch of learning how to improve and protect peoples’ health. Telemedicine is medical care transferred to distance using modern technology and telecommunications.

2.2 Types of Telehealth Systems

There are few classifications of telehealth systems that were found in the literature.

One of them is*Products and Pricing - Lifestyle Health Systems* (n.d.), it is based on systems functions and technological complexity:

Remote Care Monitoring Such type of systems monitor someone in their living setting during 24 the hours a day and 7 days a week. The goal of the remote care monitoring systems is to ensure whether someone is safe and well. Systems collect and record information about a person’s activity and health through the wireless, small, camera-free sensors which are strategically located in a home or the living quarters. The system can alert a family member, care giver or staff member, if there is a change in the routine or health status.

Home Telehealth Home Telehealth systems are used to provide a connection between the patient and his or her health care provider. It is a way of supporting the monitoring of patients between clinical visits. The home telehealth systems are used to read and forward the daily information about patient’s health condition. Information is sent to patient for self-monitoring or to the care providers for monitoring and review. Systems can also be programmed to analyse the received information.

Personal Emergency Response Systems Personal Emergency Response Systems are used to connect someone to a 24-hours call centre. In the case of emergency, a signal is sent from the house to the call centre, where the staff would evaluate the situation and decide whether to call an ambulance or a designated contact.

Home Automation Home automation systems are the combinations of residential sub–systems integration. Central controller operates almost all the living providing and communication sub–systems of the house, and this way making costumers' life easier, safer, more comfortable, and secure.

As current work is more related to the technical aspect of the data transfer of telehealth, rather than systems function and usage, it has to be a different telehealth system's classification. The most corresponding aim of this thesis classification is a classification based on the way of data transfer and the general goal of service Oregon Evidence-based Practice Center, Portland, OR (2006).

Store–and–Forward In some sources are also called 'pre–recorded' Lateef (2011). These systems have no requirement for the obtained information to be transferred in the real–time (as soon as it gets measured). Store–and–forward systems collect the data about patients' conditions, stores it and transfers the data to the medicine specialists. The specialists may interpret the data any time they want. Therefore, the store–and–forward type of telehealth systems is an asynchronous, non–interactive form of telemedicine. It is most often used to replace a consultation visit to clinic or hospital.

Self–Monitoring/Testing This kind of telehealth systems is also called 'Home–based' Oregon Evidence-based Practice Center (2001) and 'Home Health' ICUcare LLC (n.d.), Telemedicine.com, Inc. (n.d.). Self–monitoring/testing systems provide a remote observation and care of a patient. The data about the patient is usually accumulated at a patient's location and can be transferred to the healthcare provider. Self– monitoring/testing systems are usually used to monitor people who require frequent observation. Such people are usually with the limited mobility or chronic conditions and take the medication.

Office/Hospital–Based Are also known as 'real–time' Telemedicine.com, Inc. (n.d.), ICUcare LLC (n.d.), Lateef (2011), 'synchronous' ICUcare LLC (n.d.) or 'clinician–interactive' Oregon Evidence-based Practice Center (2001). This type of telehealth systems allow a face to face communication between the patient and the medical specialist or between the medical specialists who are at a distance. Office/hospital-based systems are created for the online consultations and visits.

2.3 Simulation Methods Used in the Telehealth Sector

This section will review the basic methods used to simulate the telehealth systems.

Over the years, the health systems have become complex, large and costly, and this process continues Eveborn et al. (2006), Wang (2009). The optimisation of the health systems is also growing. The computer simulation is widely used for many types of process evaluation, improving and optimisation Benneyan (1997). "Simulation allows experimentation with a model of a system. A model is a representation of a system or process. A simulation model is a representation that incorporates time and the changes that occur over time. Simulation allows to study how the system changes over time, and how subsystems and components interact Carson (n.d.)."

There are two necessary components of a good simulation model, numeric measures of system performance and clearness of system performance. The clearness of system performance can be reached by an understanding of the system behaviour and understanding potentials of development by a reasonable use of visual tools, and animation and sensible set of experiments and good statistical analysis.

The four simulation techniques are Monte Carlo Simulation (MCS), Discrete Event Simulation (DES), System Dynamics (SD) and Agent–Based Simulation (ABS) Mustafee et al. (2010), Brailsford (2007).

2.3.1 Monte Carlo Simulation (MCS)

MCS is a motionless, fixed simulation technique which completely ignores the temporal dimension Sadoun (2000). MCS model consists at least one random component. MCS approach is used to model probabilistic happening when characteristics changes don't depend on time value Lawson & Leemis (2009).

MCS technique is used in medicine research when there are technical or moral limitations. For example, experiments on human beings Ricci et al. (2009). In these cases, event probability data usually is assumed from experience.

MCS is employed to assess health risks. The goal of such studies is to evaluate the chemical or containment interaction with a person. Some studies focused on environment pollution and food poisoning. Some studies assess to develop a drug and to define a dose-response portion. MCS can determine the Probability of Target Attainment of pharmacodynamics indicators. Djohan et al. (2007)

MCS is often used for interference of medical interventions for the judgment of disease averting or disease transmission. Medical procedures and treatment reduce the disease morbidity and mortality. The goal of MCS is to find the optimum level of medical intervention, considering that usage of medical intervention costs money, and can be determined in some cases. MCS allows to model requirements for medical procedures and treatment by the assumption data from the disease and/or procedure history. MCS is also used to develop a criteria for the medical intervention risk factors classification. Sparrow (2005)

Another common application of MCS is the evaluation of cost–effectiveness of the medical interventions and health programmes. MCS can provide a cost-utility analysis of the wide varieties of scenarios, depending on a demographic transformation, planned medical treatment, medication effectiveness and individual persistence with treatment. The input data for the model are captured from the clinical studies and trials, experts' interview, and literature. The main measurement unit of cost-effectiveness is the cost per quality-adjusted life-year gained. Schwenkglenks & Lippuner (2007)

In addition, MCS can be used as a part of the different simulation techniques, then MCS simulates some parts of a system. O'Hagan et al. (2007)

2.3.2 Discrete Event Simulation (DES)

DES technique is used to understand a system performance over time by sequential events representing Villamizar et al. (2011). DES portrays single objects–"entities that move through a series of queues and activities at discrete points in time Tako & Robinson (2010)." DES has two approaches, time slicing approach and next-event approach, depending on time value representation. In time slicing approach, time flows uniformly, but in next-event approach, time value changes from event to event. Mustafee et al. (2010)

In the health context, DES is usually used for representing a patient flow.

DES is commonly used for examining healthcare services. This simulation technique allows to have the information about the clinical resources (staff, equipment) scheduling and identifying possible reorganisations of existing resources, and in this way, to improve the healthcare services. Ingolfsson et al. (2003)

DES is also employed to evaluate the economic cost of providing healthcare to population at large. Evaluation includes different healthcare interventions comparing with the goal to optimise the public health resources utilisation. Scherrer et al. (2007)

Another application of DES is healthcare work- flow processes planning and review. Aaby et al. (2006)

DES is exploited to plan and design the mass dispensing and vaccination centres, and emergency clinics. The goal of these measures is to prevent the outbreak of contagious diseases. Eidabi et al. (2000)

2.3.3 System Dynamics (SD)

SD technique is used to understand how a structure determines the behaviour, the system components relation and their influence on each other. The system elements are presented as a causal loop diagram, the elements relations as arrows between the elements, influence direction as arrows direction. “+” sign represents an element increase, but “-” represents decrease. The value of influence in System Dynamic is not important and not shown. The time value does not have an effect on SD Brailsford (2007, 2008).

In health area, SD is usually employed to examine how the basic structure can affect the demeanour of a healthcare system.

SD is used to economically evaluate the public health policies. It is applied to examine economic consequences and effect of the different public health policies Ahmad (2005).

SD does not allow to model a complete healthcare system, but only several sub-parts of a system and analyses these sub-parts interaction. It provides a potential for multiple elements of the infrastructure. This simulation technique helps to propose the public reaction to disruptions of infrastructure and disasters Arboleda et al. (2007).

Another application of SD is educational, it helps to teach pharmacokinetics and pharmacological SD Sanchez Navarro (1993).

2.3.4 Agent–Based Simulation (ABS)

ABS is used to study the behaviour of components of system, and the overall system behaviour as a result of components interactions. It contains agents and its attributes, rules which specify agents behaviour and ways of interaction with another agents Macal & North (2010).

In health area, ABS is usually used to study the spread of epidemics.

It was used to identify the dynamics and interactions of cancer hallmarks and therapies Abbott et al. (2006).

2.4 Evaluation Methods of Telehealth Systems

This section defines and discusses the approaches to evaluate telehealth systems found in the literature.

Evaluations of telemedicine systems success “centre or involve telemedicine systems and often have profound impacts on the feasibility, efficacy, viability, and sustainability of the services that they enable” Paul Jen-Hwa Hu (2002). Therefore, the telehealth systems evaluation task is transformed to telehealth services evaluation task. “If we wish to provide a telemedicine service, we should first establish that it is safe, next that it is practical and finally that is worthwhile" Taylor (2005).

Thus, the most important element of the telehealth systems evaluation is to guarantee that telehealth services provided by that systems are safe. Taylor (2005) establishes the telehealth service safety as ability to provide as 'useful' data as though they were received by a traditional way. 'Useful' is described as appropriate, precise, modern, full, and dependable. One more important property of the 'useful' data is availability, data have to be able to restored and analysed.

Data utility or quality is not a complete entity, it can be measured only by comparison according to the common standards. For the telemedicine information utility testing, the experiments need to be carried out. For the accurate results, these experiments need to be carried out in identical conditions for the telehealth and non–telehealth interference. The experiments results are relevant to technical features and medical condition. For example, lighting settings, image resolution and showing, ergonomics, and data transmission speed Vidmar (1997) can affect the experiments results.

To familiarise with requests and to satisfy requests to data quality and telehealth system, safety is ensured by following the guidelines, protocols, care pathways, and clinical guidelines.

There are many different factors that can complicate the interpretation of the experimental results. One of the most important factors is medical personal's technical incompetence, they may not be aware of the telehealth devices and procedures. However, an appropriate medical education and training could solve this issue.

The other fundamental problem is that health professionals are accomplished to work with specific types of information. For example, subtle lesions were detected more often on x–ray films by radiologists than by using the digital monitors. Of course, in this case, non–telehealth data is much more useful than telehealth data. But at the same time, the effect of the loss of information can outweigh the benefits. If there are patients who cannot get healthcare otherwise using of the telehealth systems, the implementation of systems will be very useful and deserving.

Gerbert (Gerbert et al. (1996)) studied General Practitioners (GPs)' and specialists' skills to detect skin problems. The results of experiment show that GPs failed in 40% of the cases, but professionals 26%. This experiment pushes a thought that the less qualified personal gave wrong results more often than more qualified. The suggestion to increase the safety is to connect GP and dermatologist. A telemedical link between GP and a remote dermatologist will improve the safety of the procedure. The link can help to a GP to achieve the same level as a specialist quickly.

A clinical, economic, technical and political aspects can affect the viability of the telehealth systems.

A very important factor of the telehealth system's success is a patient satisfaction. Patients work with the telehealth system more often, and happily if they are satisfied with the system. Some features making the healthcare systems more attractive for patients aspects are described below. Patients would want to be able see and hear clearly during the teleconsultation session, and to be sure, the teleconsultation is confidential. Patients need to believe that the telehealth system provides a consultant with appropriate information to make trustworthy conclusions about their condition.

Publication INSTITUTE OF MEDICINE (1996) describes some aspects to assess a telehealth systems quality and outcomes. These aspects analyse the telemedicine and traditional treatment and involve:

1. quality differences, quantity or sort of data accessible to patients and health professionals
2. variation in patients' familiarity with their conditions and treatment alternatives understanding and apprehending
3. variety in distinguished precision or opportuneness
4. differences in death frequency, morbidity, or mortality
5. urgent, middle and long–term results of the telemedicine care

The cost effectiveness of telemedicine is a very important aspect used for evaluation and comparison. The applicability of the telehealth interference is not enough for a common approval, the costs of treatments using different methods should be carried out. To create a method to divide expenses precisely, is very hard. Diseases healed using telehealth systems are also healed by the alternative techniques. Usually the telehealth systems complete or compose existing methods and use the same resources, therefore, it is hard to define the telehealth costs. Normally, the apparent economies of scale determine the manufacturing costs. The publication Allen & Stein (1998) provides the detailed report of cost efficiency across the telehealth applications field. These authors' opinion is the healthcare for the prisons and homes, telepsychiatry and teleradiology are usually cost effective, as a lot of examples show. But the nature of some asserted cost savings are not clear, some of them were avoided or undervalued, but benefits cannot be defined conveniently. The publication McIntoch & Cairns (1997) is generally devoted to the economic evaluation of telehealth. The publication defines the central evaluation challenges and economic points, and then the publication continues to consider questions that connect the expenses and consequences. The Hailey et al. (1999) provides a more generalised approach to evaluate the telehealth care, this method was applied to the application of the real telepsychiatry system in Canada. The method evaluates telehealth system considering the five factors: specification, execution marks, results, total measures, and functional. The consideration is also provided in this publication. It was discovered through the method application results that the system provider does not have any cost benefits, but patients have an important service price decrease.

2.5 Comparison Methods of Telehealth Systems

This section is devoted to the definition of the most appropriate ways of comparing of the telehealth systems.

Any IT enabled system (including telehealth system) can be organised in a multitude of ways, deploying a multitude of hierarchies.

However, as there are distinct reasons for the telehealth system concept to be of interest for our society as a whole (namely, economic reasons, efficiency and potential healthcare quality improvement), it is reasonable to expect to have an ability to compare the telehealth systems. For society to be able to take advantage of a best possible solution (or solutions).

Just as any other economic entity, the telehealth system is interacting with several bodies each of whom has its own preference regarding the efficiency methods:

- Investor, who is interested in the economic efficiency of the system
- Consumer, who is interested in the quality of service that system offers
- Society is interested in for all the medical services to be ethically reasonable.

It is worth noting that it is possible for any real life structure to possess a stake in any of the points mentioned above. Foe example, if one assumes government as an intrinsic part of a society, and if the telehealth system had been built and maintained by the government, than 'society' will effectively be holding a stake in both 'economic efficiency', 'wide availability' and 'ethically reasonability'.

As there are three general aspects to the any telehealth system operations, one might expect for industry to have the measurement procedures and practices to measure a potency of any telehealth system in given dimensions.

2.5.1 Economic Efficiency

As for any other type of system, the ‘economic efficiency’ of the telehealth system can be measured using the finance industry standard practices: Cash Flows, Internal Rate of Return (IRR) and Net Present Value (NPV) metrics.

Due to the nature of healthcare, it is not necessary for the investor to expect a profit from a telehealth system. But, even with a non profit investing entity, it is reasonable to expect for a given entity to seek ways of expense minimisation.

Given scope of the current work, it had been considered unnecessary to provide an in–depth description of the economic metrics in question, but it is worth noting, however, that any project has three distinct phases:

- Setting up cost (or upfront investment)
- Production cash flow[1]
- Salvage value[2]

It is reasonable not to expect for healthcare related project to have a substantial salvage value as healthcare is a service that any society (and humanity as a whole) have the perpetual need for, so most likely, any healthcare related project will be exploited until technological advance yields an alternative, that is by an order of a magnitude more efficient than the old system. Usually it takes decades for technology to be able to make such an offer.

2.5.2 Quality of Service

Most modern healthcare consumers expect the healthcare system to offer a certain level of quality of care. This includes quality of diagnosis, convenience of interaction with a system, emotional comfort of communication with health professionals, and convenience of participating in the project.

It is yet uncertain what maximum diagnosis quality the telehealthcare system will be able to offer, and how it compares to the conventional healthcare Gerbert et al. (1996), INSTITUTE OF MEDICINE (1996). The general motto seems to be that more data is better than less data, and the telehealth system deployment does unlock the ability for the health system to collect much more data on any patient’s condition. It is reasonable to expect this data to be of use not only for remote diagnosis procedures, but also for the usual face to face healthcare sessions, given the

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[1] This usually includes maintenance cost, operating profits and other expenses

[2] Cost of selling all project equipment at the end of a project

developed procedure of interaction between the conventional healthcare and the telehealthcare institutions.

As of convenience metrics, one can expect for the telehealthcare to be noticeably superior to the conventional approach, due to the lack of queues and no need to travel to interact with a system.

'Emotional comfort of communication with health professionals' is actually a staff management problem that involves a lot of various elements and has been addressed in all large institutions NHS Grampian (2012), The University of Western Australia (2003). Thus, it is reasonable to expect this problem to have metrics of its own.

'Convenience of participating in the project' aspect is an attribute of reflection of internal projects' workflow on its customers. It involves the ease of rolling in and out of the project as well as the ease of routing procedures any participant has to follow to provide data needed by the system. It is possible to address this problem using extensive usability studies.

2.5.3 Ethically Reasonable Medical Service

Since early 19th century, Percival (1803) medical services have been at the centre of ethical debates Baker & McCullough (2009).

There are various ethic questions that the community has to decide on when in comes to the healthcare system: 'Is cost–effective analysis of healthcare procedures ethical?' Williams (1992), 'Is compulsory medical treatment ethical?' J. Silber (2011), Meier-Allmendinger (2009) and many others.

But it is authors' belief that it is unethical to knowingly expose the patients to the healthcare service of inferior quality. This decision is much similar to the reasons why Food and Drug Administration (FDA) can terminate any human drug testing prematurely if the drug's efficiency had been noticeably below the expected level (FDA 2012, Section 312.44, point 2(iii)). Thus, it is possible, one is ethically obliged to compare and evaluate the telehealth systems to avoid patient exposure to the sub–quality treatment.

2.6 Research Gap

The literature review has discovered the importance of proper design in the telehealth systems. It has also discovered the potential of the simulation tools to assess the existing healthcare system. However, there has been no work carried out that investigates the use of simulation tools to assess telehealth systems. The aim of this project is to develop a method to evaluate and compare the existing telehealth models using DES. Thus, it will be a useful contribution to knowledge.

Chapter 3

Methodology

3.1 Simulation

It is important to know the characteristics of systems, to be able to evaluate and compare them. To perform a rigid and repeatable simulation, the analysis and comparison of a set of systems, the behaviour of the systems analysed has to be expressed in a non obscure way, in the form that could be subjected to the statistical apparatus. Thus, all measurements taken upon any system being compared, have to be expressible in the numerical domain.

The publication Adeogun et al. (2011) contains information about twelve telehealth systems which are used in the United Kingdom, to monitor several chronic conditions. The author of the publication uses the term, ‘offering’ meaning the more traditional term ‘system’. Thus, in current thesis, words ‘offering’ and ‘system’ are used as the equal terms. The publication Adeogun et al. (2011) provides twelve data flow diagrams of the telehealth systems with a brief description of the behaviour of the each system.

The publication’s Adeogun et al. (2011) information and specifics allow to build only DES models. For example, SD models do not provide numerical evaluation of system performance and it is known that these systems are operational, therefore, SD Simulation approach is unsuitable for evaluation of the given systems. DES modelling approach reflects behaviour of real life systems, and allows to get the numerical measurements of the models’ properties, and exhibits the characteristics of real life systems’ performance.

It is impossible and redundant to create the full simulation of a system, featuring each and every minuscule detail of it. In the end, to make such a thing one has to create an exact physical copy of a given system. In order to make a comparison of the systems, same measurements of performance need to be used amongst all the modelled systems. Because of that, it is logical to develop a methodology for the building of DES models to unlock the ability to get the chosen systems performance characteristics. For this reason, the methodology had to be developed to convert the twelve data flow diagrams into the DES models.

3.1.1 General Approach

Four books from Pidd (2004), Robinson (2004), Banks et al. (2005), Law & Kelton (1991) on simulation were assessed for the description of modelling process steps. All those books describe the same modelling process steps. Therefore it had been assumed that the methodology of the simulation model building that is described in them is a de–facto standard. However, the described process steps are only a general guideline, because the "construction of a model is probably as much art as science" Banks et al. (2005). From this follows, that the DES building methodology field–specific and the common modelling process steps are used a as general guideline.

The main model building steps are:

1. To establish an comprehending of a problem situation (define terminology, create precise definition of the problem)
2. To define the modelling objectives
3. To build the conceptual model
4. To accumulate and review the data needed to build the model

Usually, the model building process starts with a definition of a problem (as it is the first step of the model building method). The problem formulation means to formulate the reason, goals of the simulation, and why the simulation is required. Without this step, it is possible for the simulation process to be not effective: as there will be chance of getting meaningless results from the model or invest much more time and money than necessary. (Usually modeller gets the problem's concept from customer and identifies and specifies problem formulation by the means of further Research.) Modellers usually work in a close collaboration with people who provide the data and information about the system work. Thus, it allows an understanding the problem in more detail, and to introduce the amendments in a problem formulation, if they are needed. The main reason and goal of the simulation in this work, is the telehealth systems' evaluation and comparison.

The modelling objectives are directly connected with the problem formulation. In fact, the modelling objectives are sub–goals that help to achieve the main goal. To determine the modelling objectives, the main goal is divided in to several smaller intermediate aims. In the case of this work, to evaluate and compare the telehealth systems, it is necessary to get the characteristics of the systems' performance.

In this work, following characteristics were chosen in order to evaluate and compare systems being modelled: maximum and average time of the entity in the system and the system throughput. These characteristics will be acquired from the future simulation runs.

3.1.2 The Conceptual Model Design

The conceptual model is a non software definition of a real world system. The conceptual model design is the most ambiguous part of a simulation process. This simulation step can vary depending on any each case. The main task of a conceptual model design is to build the simulation model, which will provide a data to reach modelling objectives. Therefore, this process is field–specific and it is unlikely that it will be possible to get a detailed universal guidance on how to perform it. However, some general recommendations are available Law & Kelton (1991), Banks et al. (2005). The recommendations are to start with a less detailed model and to sophisticate it until the model achieves the simulation objectives.

DES was chosen to achieve the simulation objectives. The DES is the type of simulation approach, that marks out the interaction ways between system elements Pidd (2004). DES model represents the entity path through queues and activities Tako & Robinson (2010). In the case of the work, the entity that goes through the whole system is the patient tests results or, in other words, the piece of information about a patient health condition within certain period.

The source of information about the work of all twelve telehealth models, that are provided within this work, is the publication Adeogun et al. (2011). In fact, the twelve models described in that publication are treated as the conceptual model designs within this work. As a result, twelve DES models are generated. The common conceptual model–building algorithm was developed for all twelve telehealth conceptual models building. This process is likely to be common when building DES for any telehealth system. The algorithm is represented in the flow chart form for the clarity and understanding. This flow chart shows the DES process for a single telehealth system, but it is applicable for any of the twelve systems from publication Adeogun et al. (2011).

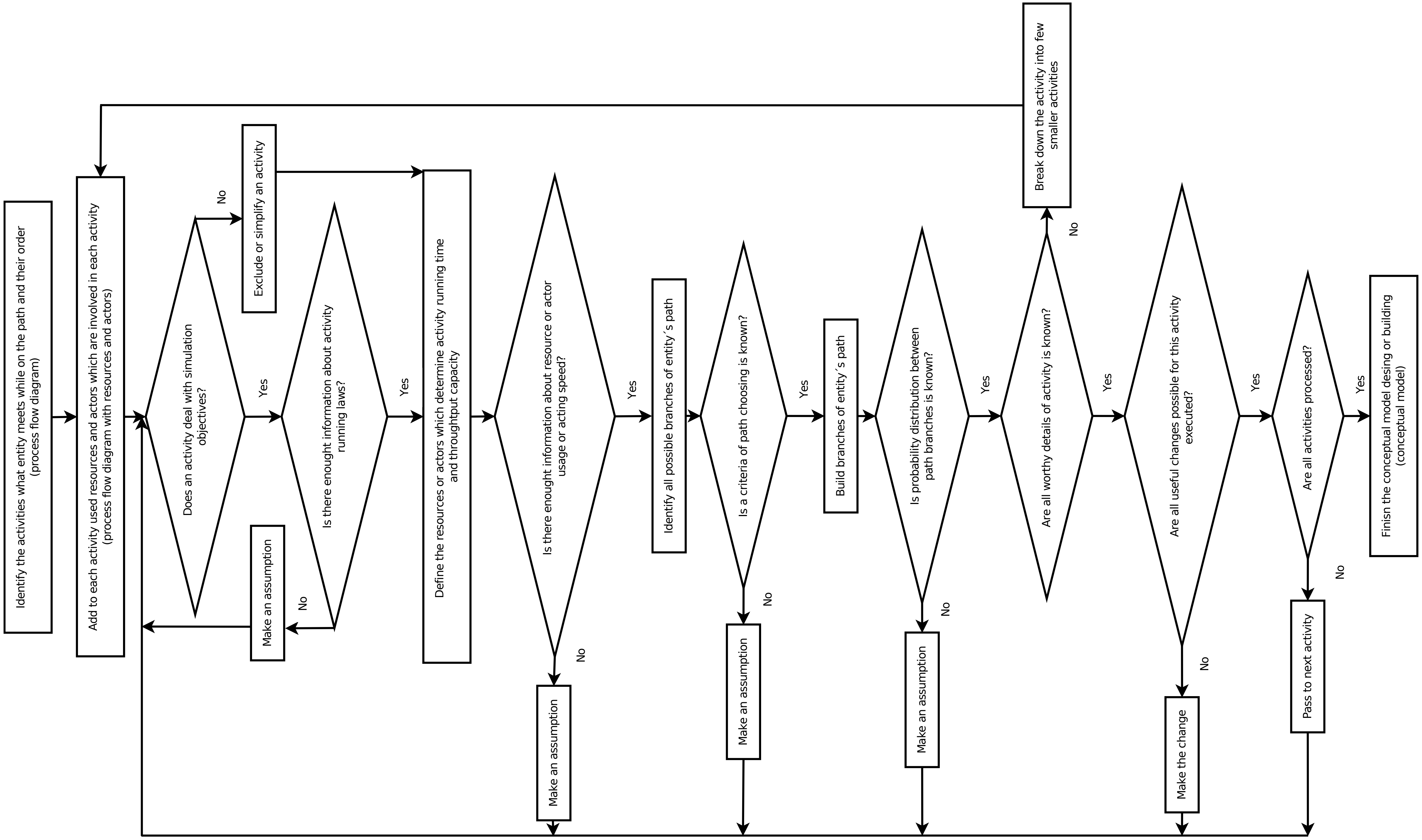

Figure 3.1: Flow chart of conceptual model building

The specifics of the DES and the general recommendations (subsection 3.1.1) forces to start the conceptual model building using top–down approach. As it usually is with the top–down approach, the procedures starts at the highest level of abstraction and iteratively moves to the lower levels of abstraction using following steps:

1. Separation of higher order entities (belonging to the above level of abstraction) to the lower order entities for the current level of abstraction
2. Introduction of resources used by the entities on the current level of abstraction

These steps can be repeated any number of times. The process stops at the moment when modeller decides that any further increase of precision does not provide any noticeable amount of added value. This top–down approach helps to achieve very important and useful objective – the breakdown of the large and complicated entity handling process into the the several smaller activities which can be considered separately and independently.

In case of this work it had been decided to use system process flow diagrams from Adeogun et al. (2011) as the description of modelled systems at the highest level of abstraction. Of course, it is not enough to know of the sequence of basic activities in the system to build the DES conceptual model. Creation of DES model also requires for modeller to define the speed of the activities (or their handling time). While the speed of the activities is dependent on the shared resources given activities are using.

As can be seen from what was written above, the conceptual model building can become complex and time consuming as process descends to the lower levels of abstraction. To avoid unnecessary investment of time and work it is recommended to stop process of descending levels of abstraction at the certain level. And even on the higher levels is useful to check if there are any activities that are not obligatory for the achievement of modelling objectives. Cutting off unnecessary activities is beneficial because it helps to limit exponential growth of entities at the lower levels of abstraction.

When only the worthy activities remain the activities may be studied in more detail. The information about the activities is seen in publication Adeogun et al. (2011). The desirable information needs to consist a data about the activities starting, ending point, resources and actors, which determine the activities running. Then, having this information, the activities running process, the activities regularities and the speed of each activity are noticeable.

The publication Adeogun et al. (2011) does not contain enough information about such aspects of the activity running. In this case, the assumptions have to be made. The procedure of assumptions making is hardly definable, because it is difficult to strictly define channels of information that will be used for acquisition of required data. For this work, it was decided to apply the following approach described below. Firstly, attempt to make an assumption basing on the context of the model. Secondly, attempt to from the available general description of the process. If first two steps were not sufficient collect enough information to make an assumption, the data about common or any way of usage resource would be used.

Then even when that information is not available or too ambiguous, it is acceptable to make an assumption for what seems logical or suitable. The assumption making procedure concerns all assumptions. This procedure allows the approaching model to the real–world system the most. Of course, the created model can differ from the real–world system, but the goal of the work is to develop the methodology and the work does not apply at all on the same real–world model building. In practice, the modellers have an access to the wider and complete issues of information about the real–world system work. In this work, the assumptions needed to be made, but in practice, the modellers usually get the necessary information from the interviews.

When any assumption is made, it is useful to check if some details can be excluded, simplified or included in some other blocks. Moreover, leftover elements are considered more deeply, and in more detail. Until there is no clear information about the activities running regularities, activity speed and every single element cannot to be excluded or simplified. The author is convinced that activities, which proceed linear, it is, the actors and resources that are always available to them, the activities always require the same resources and actors, that do not contain the branches and do not require some special conditions, they have to be simplified or included in some other activities, or combined if they occur in a consecutive order. In this case, the speed of such activities also needed to be included in some other activities speed, or combined together. Thus, the results of this process need to be a clear data about each activity speed and the representation of activities running regularities.

As it is a DES conceptual model building methodology, it is the entity path through the whole system representation building. That is why another important kind of elements can appear in the conceptual building – the entities' path branches. It is useful to identify all possible branches of entities' path and to understand the path choosing criteria. The information about path choosing criteria should be in publication Adeogun et al. (2011). But even this information can not be included in publication Adeogun et al. (2011). Then the assumption about the path choosing criteria is needed to be made. The procedure of assumption making is appropriate for this kind of assumptions too.

The process of conceptual model building is cyclic. After every assumption making, deeper level reaching or any change in conceptual model, it is important to return to check if any element can be excluded, simplified or included in some other element. Then the process starts again from the checking point of conceptual model building flow chart.

This process of conceptual model building continues until any useful changes in conceptual model cannot be made, conceptual model represents the activities running lows and the speed and throughout the capacity of each left element is clear.

The result of the described DES conceptual model building procedure is the flowchart of entities processing procedure in a system. Then it is possible to convert every single flowchart's element into a single element in a simulation software. The desirable conceptual model is created.

3.2 Building Computer DES Models

3.2.1 Choice of a Simulation Tool

The selection of simulation tool was based on the following criteria:

1. Discrete Event Simulation approach support
2. Support of selection with probabilities
3. Ease of use
4. Extensibility
5. Documentation and support
6. Cost of acquiring a license

AnyLogic simulation tool has been chosen because it supports DES technique. In addition, the AnyLogic has built–in selection elements that work at a basis of probabilities. The AnyLogic provides the wide range of in-built elements and helps to save time. The AnyLogic supports not only the drag and drop method of the simulation model building but also allows extensibility, including the custom Java code. The AnyLogic also provides easy to use means to add animation to the visualisation of a model. The model execution speed can be increased considerably. This tool has a good documentation and help service. Finally, Cranfield University has a licence for the AnyLogic tool.

3.2.2 Computer Implementation of the DES Conceptual models

As simulation software was chosen the AnyLogic, and this section of the thesis is devoted to the conceptual models' elements conversion into AnyLogic models' elements. The conceptual models contain the limited range elements types, and it is enough to show examples of these conversions.

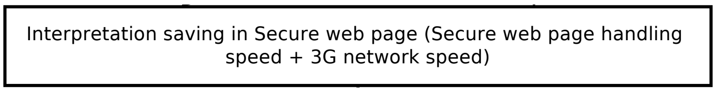

Figure 3.2: Example of the activity in the conceptual models

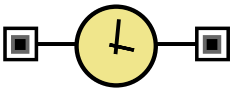

Figure 3.3: Example of the activity in AnyLogic

Activity is the most common element in the DES conceptual models. Activity proceeds linearly. In the DES conceptual models is represented by Figure 3.2. An AnyLogic element which is the most suitable to define activity is Delay in Figure 3.2. Minimal, maximal and the most common time of activity processing can be defined by a triangular (min, mode, max) function.

Process Flow Direction element is an integral component of DES models. It shows the direction of entity's path. In the DES conceptual models Process Flow Direction element looks like in Figure 3.4. The AnyLogic equivalent to Process Flow Direction element is Connector in Figure 3.5.

The DES conceptual models start with entity arriving element, it is the beginning of a simulated process. The DES conceptual models contains such type beginning elements in Figure 3.4. The AnyLogic models' starting point is Source element in Figure 3.5. A Source generates entities and allows defining entities' arrivals in models.

Every DES model's end is entity–leaving element, it is the finishing point of a simulated process. There is the representation of entity leaving element in the DES conceptual models in Figure 3.8. An AnyLogic process finishes when entity reaches a Sink element in Figure 3.9. A Sink element disposes entities.

Entity's path branches are very common in DES model (such branch is depicted in Figure 3.10). Usually the entity's further path depends on some entity's feature or some condition. In the DES conceptual models from this work the entity's further path is often defined with a probability. The AnyLogic element which supports all those singularities is a SelectionOutput element (Figure 3.11) for the selection from two ways and more (Figure 3.12). The SelectionOutput element routes the incoming entities, the direction can be defined by a condition or

Figure 3.4: Example of Process Flow Direction in the conceptual models

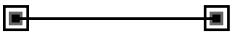

Figure 3.5: Example of Connector in AnyLogic

Figure 3.6: Example of Entity arriving in the conceptual models

by using the probabilities. The AnyLogic supports the additional parameters of entities and the changing parameters' values. It can be done very easily by using the basic principles of object–oriented programming approach. Code has to be written in Java.

Necessary element of every DES model is a queue. It is an obligatory element before the activities what have a limited capacity. A queue's form in the DES conceptual models is Figure 3.13. A corresponding AnyLogic element exists, it is element Queue (see Figure 3.14).

There is a common activity which uses the defined number of common resource units in DES models. The example of such activity from DES conceptual models is Figure 3.15. A Service element provides the suitable functionality in AnyLogic. It is the obligatory element before activities with limited capacity. The Service element requires to define a number of resource units needed to process activity, and activity processing time. The triangular (min, mode, max) function for definition of minimal, maximal and the most common time of activity processing is also available using the Service element. The Service element has to be accompanied by ResourcePool. A ResourcePool determines a type and capacity of the resources. Service and ResourcePool look like Figure 3.16.

More complicated case is when an activity requires several types of resources or when activity processing is not linear. Such activities come across the DES conceptual models Figure 3.17. AnyLogic has tools to simulate these complicated cases. AnyLogic uses Seize and Release elements to seize the resources for entity processing and to release the resources after processing. The seize element functionality is similar to the Service element but the Seize element does not provide a functionality to define the activity processing time, an activity processing is defined between the Seize and Release elements using the elements standard AnyLogic simulation elements. The example is represented by Figure 3.18

The DES conceptual models require to use the priorities (Figure 3.19). AnyLogic supports

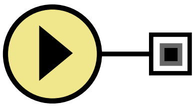

Figure 3.7: Example of Source in AnyLogic

Figure 3.8: Example of Entity leaves in the conceptual models

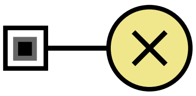

Figure 3.9: Example of Sink in AnyLogic

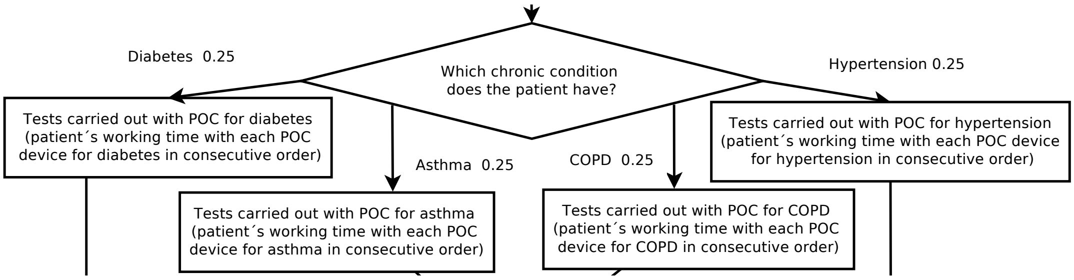

Figure 3.10: Example of entity's path branch in conceptual models

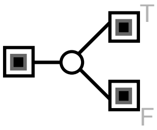

Figure 3.11: Example of SelectionOutput for two ways in AnyLogic

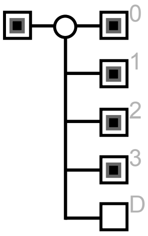

Figure 3.12: Example of SelectionOutput for more ways in AnyLogic

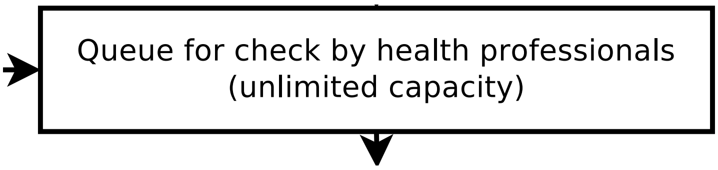

Figure 3.13: Example of queue in conceptual models

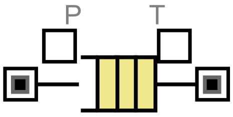

Figure 3.14: Example of Queue in AnyLogic

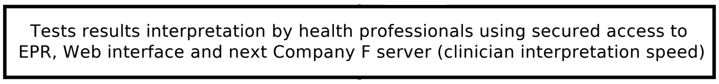

Figure 3.15: Example of resource seizing in conceptual models

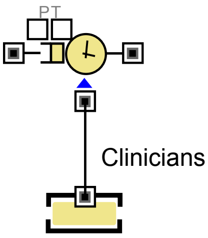

Figure 3.16: Example of Service and ResourcePool in AnyLogic

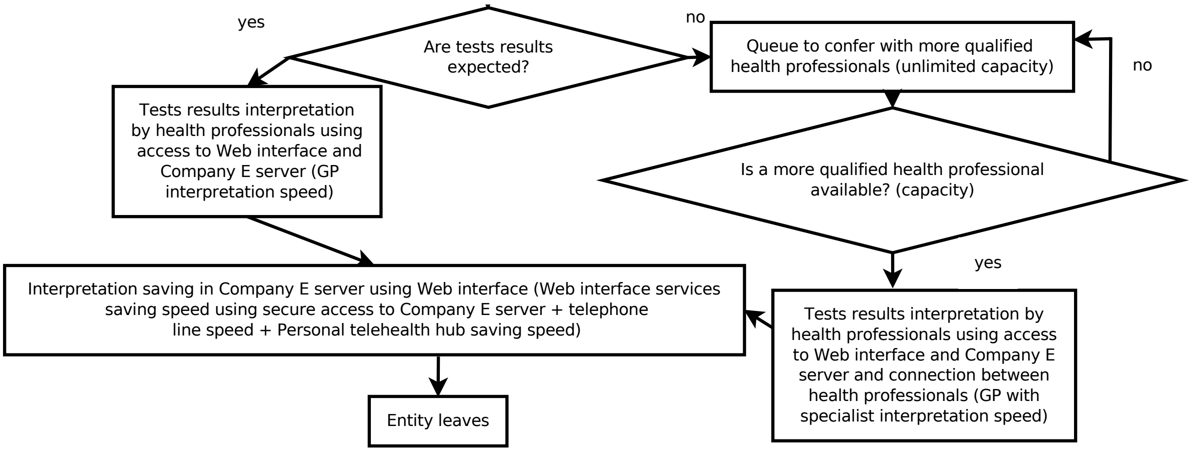

Figure 3.17: Example of several types of resources using branching for activity processing in conceptual models

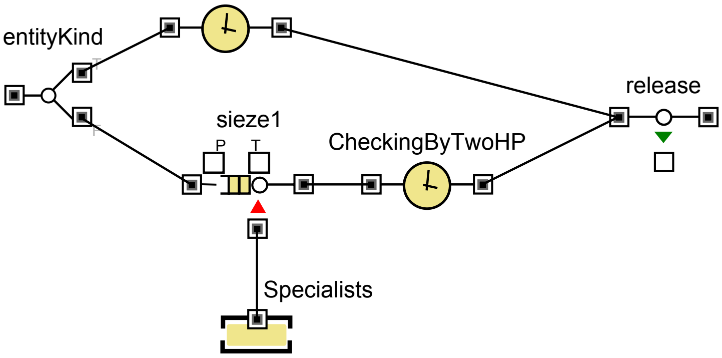

Figure 3.18: Example of Seize and Release in AnyLogic

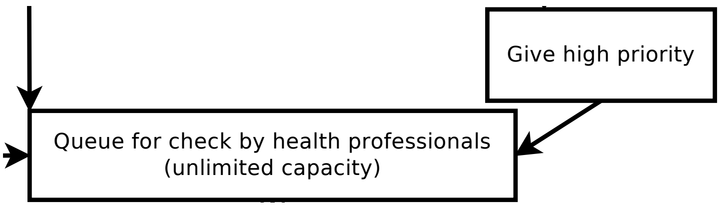

Figure 3.19: Example of priority using conceptual models

priorities as the additional parameter of entity, and providing the queue's sorting by entity's parameter in-built functionality.

This list of conversions is sufficient to create the AnyLogic DES model for every offering from Adeogun et al. (2011).

3.3 Evaluation

As it has been previously discussed in section 2.5 "Comparison Methods of Telehealth Systems" (see page 22), there are three dimensions of interest to every telehealth system:

- Economic efficiency of the system
- Quality of service
- Ethicalness

To unlock the ability to make the comparison of the telehealth systems, it is necessary to map systems properties, in each of these dimensions to the numerical value.

3.3.1 Economic Efficiency

The dimension of the telehealth system is 'Economic efficiency'. It is intrinsically understandable that there are three major stages of how the system works (below) and each of these stages has certain expenses attached to it.

- Birth: Telehealth system construction
- Life: Routine operations of a system
- Death: Systems' disassembly

Regardless of an investor supporting the system, it will be attempted to minimise a ‘price tag’ of each stage of a systems’ life time. Whenever an investor will seek a positive end balance (making a profit) or not, is dependent on the particular telehealth system.

With no particular system to work with, it is impossible to evaluate the costs of systems’ creation and destruction, as the cost will be heavily dependent on the architecture used and on the economic circumstances. Arguably as the telehealth system is usually created to serve as many customers as possible, it should be built to last. Thus, the major source of expenses will be life time expenses. In the life–time of a system, ‘staff costs’ are actually accountable for the largest share of the medical institution expenses. For example, in the 2010/11, the North East National Health Service (NHS) spent £$4,803,162$ or about 70% of its £$6,870,698$ budget on ‘staff expenses’ NHS North–East (2012) and Northampton General Hospital NHS trust paid £$121,300,000$ or 67% of its £$181,049,000$ 2008/09 expenses as staff costs (Northampton General Hospital NHS Trust 2009, page 15). Both of these expense disclosures included the medicine supply purchases as their second highest.

Thus, in current work, it is considered that most of expenses for telehealth system will come from paying the staff salaries in same way as it is occurring in NHS. It is also viable that in case of the telehealth system, salaries will represent the biggest share of expenses than in face to face NHS business model, as it is not expected for telehealth centre to purchase the noticeable amounts of medical supplies.

3.3.2 Ethicalness

It may be impossible to map some dimensions of a system to a certain numerical value. In the current case, an example of such dimension would be ethicality. It seems unlikely that an algorithmic procedure to map ‘ethicality’ of the system to the number axis can be developed. Due to the nature of the beast in the question. Ethics is likely to remain in the domain of unquantifiable human emotions for the foreseeable future.

3.3.3 Quality of service

The ‘quality of service’ metrics is the most definitely quantifiable as it is demonstrated by e–commerce vendors Volter & van Moorsel (2001), hotel management V. Hill et al. (1998) and calling centre management NAQC (2010).

Examples of quality of service metrics are:

1. Performance
2. Degree of fault tolerance

3. Completeness
4. Accuracy
5. Capacity

(example is attributed to Brown (2000)).

Although given examples were originally mentioned in the context of the IT systems, they can be adjusted to a telehealth institution as well. Exempli gratia, ‘degree of fault tolerance’ metrics can be used to measure what percentage of staff is absolutely necessary to maintain the basic system functionality (or how many staff access points to the Information System have to be in good working order at any moment of time, for the system to be able to function), and ‘Capacity’ can be used to measure the maximum number of customers at a given centre can serve with constraints such as maximum performance of the central processing server, or the maximum number of staff that can be deployed in the current centre building.

Sadly, it is impossible to develop and test full–scale measurements for ‘quality of service’ dimension within scope of current work due to the time and budget constraints.

However, it is possible to make certain assumption on some aspects of ‘quality of service’. Similarly, with call centre metrics described in NAQC (2010), it seems reasonable to expect the controlling process to minimise an average time it takes to process single result. In line with both approaches described in the call centre metrics publication and perceived medical need, it also seems reasonable to limit the maximum time it takes a telehealth centre to process the incoming patients’ results. The management motivation for that is to control a variation of the result processing times, so the average time would not be an average of sub–second processing times, and one result that it had, took a year to be processed. Medical reason to introduce a hard limit on the result processing is that healthcare is inherently risky, there is always a risk that patients’ condition is (or soon to be) critical with patient not noticing it until it is too late. Of course, at home telehealth monitoring is not currently considered to be an adequate care approach for patients in a critical state of health, but one can assume that it is the ethical responsibility of a monitoring entity to call in emergency care for critical condition of an organ or bodily function it is monitoring.

For the sake of simplicity, it was decided to stick to a limit of 2.5 hours, as it is an average time for a London ambulance reserves to react for ‘urgent’ (but not life threatening) calls, Office for National Statistics (2011*a*).

3.3.4 Summary

While summarising this section, it was decided to make an explicit list of metrics that are going to be used in the current work for telehealth system evaluation:

- Minimisation of average time it takes to process a single result[1]
- Minimisation of a total sum of staff expenses[2]
- Limiting the maximum time it takes to process a single result to two and a half of hours[3]

Considering a constant system state, it is realistic to expect an average and maximum time in a system to increase with the density of the incoming result stream. It is also expected that average and maximum times to be very small, when small number of incoming messages arrive.

In addition, one could expect a maximum processing time to decrease by an increase in the staff count (assuming no intrinsic inefficiency of staff).

Thus, the problem of applying a limit for a maximum waiting time and an aim for an average waiting time reduction has to be, introduced by the fixed number of incoming messages and staff between the all systems compared for the system comparison to be correct.

3.3.5 Metrics Used

Not all of the twelve telehealth systems compared deploys same the type of staff. To resolve this issue, it was decided to use as close numbers of staff as possible, and to calculate an average message processing cost, instead of a total running cost. For example, given that m messages have arrived within a time period t (hours) and the running cost of a given centre is £x per month, the average cost of processing P_{avg} will be calculated using Equation 3.1.

$$P_{avg} = \frac{x}{157.72} \div \frac{m}{t} \tag{3.1}$$

This formula has been introduced assuming 36.3 working hours per week (UK national 2011 average, Office for National Statistics (2011*a*)) and 4.345 weeks in a month Wolfram|Alpha (2012). Therefore, there are $36.3 \times 4.345 = 157.72$ working hours in an average month.

As an income result density, it is worth noting that considering everything else fixed, for each telehealth system there is a critical income message density above which a system cannot guarantee the ‘maximum processing time’ limit. This message density will be called ‘saturating input density’ in the current work.

---

[1] ‘Average time in system’ in DES terms

[2] Used as an estimate of systems’ operating cost

[3] ‘Maximum time in system’ in DES terms

With many systems to compare, it makes sense to make a comparison of saturating input density for each system, so it would be possible to see what organisational approach is most prone to the message delay.

In addition, two additional measurements of systems' parameters will be made on 80% and 50% of the systems' saturating input density to get a sense of behaviour dynamics.

To summarise, for each of twelve systems, following measurements will be taken:

- Saturating input density
- For each of 100%, 80% and 50% of the saturating input density:
  - Results' average time in the system
  - Results' maximum time in the system
  - Single result processing cost

3.4 Comparison

As all metrics that are used in current work are numerical, it is possible to make an unbiased comparison of them. However, to compare systems as a whole is a more challenging problem.

In scope of this work, it seems to be impossible to assign preference to any of metrics, thus it is impossible to use simple one–dimensional comparison approaches like weighted average.

There is, however, comparison system that have been developed to satisfy such needs. It is 'Pareto efficiency' – a concept named after Vilfredo Pareto (1848—1923), Italian economist.

In a nutshell, if there is a set of entities with each entity having vector of metrics that are being minimised, the Pareto front $\mathfrak{R}^*$ of $\mathfrak{R}$ is a set where each element belonging $\mathfrak{R}^*$ also belongs to the $\mathfrak{R}$ and each part of any $\mathfrak{R}^*$ elements' metrics is 'more optimal'[4] than any element in $\mathfrak{R}$ set.

Thus, in scope of this work, it have been decided to compare DES simulation results using Pareto comparison and to produce list of models belonging to the Pareto–optimal set (also called 'Pareto front' and 'Pareto frontier').

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[4] Less or equal in case of minimisation problem, greater or equal in case of maximisation problem

Chapter 4

Results

This section shows the results of the applying of a methodology described in Section 3.

The simulation process starts with the simulation model building. The conceptual model design method 3.1 was applied to build conceptual DES models. The description of this process is in Section 4.2.

During the building process, the lack of data about the system work was discovered. Because of that, there was a need to make several assumptions about the internal organisation of telehealth systems being modelled, the timings and prioritised features of actual systems to be reflected in the constructed models. There are three sections devoted to the assumptions: section A.1 “Simplifications Required for Model Building” (see page 119) lists the assumptions made during the building of DES conceptual models, and concern the model architecture, section A.2 “Device Usage Data” (see page 129) and section A.3 “Staff Data” (see page 134) contain the assumptions about the speed and amount of elements of DES conceptual models. The Table A.3 “Point–of–care device (POC device) deployment vs condition” (see page 128) represents the list of POC devices deployed for monitoring any of the conditions that are subjected to the modelled telehealth systems. The Table A.1 “A list of assumptions applied to the Offerings (Part 1)” (see page 125) and Table A.2 “A list of assumptions applied to the Offerings (Part 2)” (see page 127) gives evidence of the connections between the assumptions from section A.1 and offerings.

To convert the DES conceptual models into the computer models, the method from 3.2 was used. The AnyLogic DES models can be found in Appendix B of this thesis.

The section 4.3 provides the modelled telehealth system simulation results based on 3.3.

4.1 Interpretation Time

It was discovered that an interpretation time was required to build the DES models.

The DES model also requires for modeller to define how long it takes for any given staff member to evaluate a single patient's results. As such statistics do not seem to be available at the moment of development of current work, an assumption had to be made.

One would naturally expect for more qualified staff member's (GP/Speciality Doctors) analysis time to differ from the less qualified staff members (nurses). Nevertheless, the actual difference in time is much harder to decide on. In models with a waterfall work model, where more qualified staff receive only results marked by the less qualified staff as unexpected, it is natural to assume that the result analysis done by more qualified staff to take more time than it takes for less qualified staff to mark it as 'unexpected'. However, for models where more qualified staff reviews the complete stream of inbound results, it is reasonable to expect the doctors to be faster than the nurses, as given small share of the unexpected results, doctors should be faster when it comes to decide if current result is within the 'expected' boundaries or not.

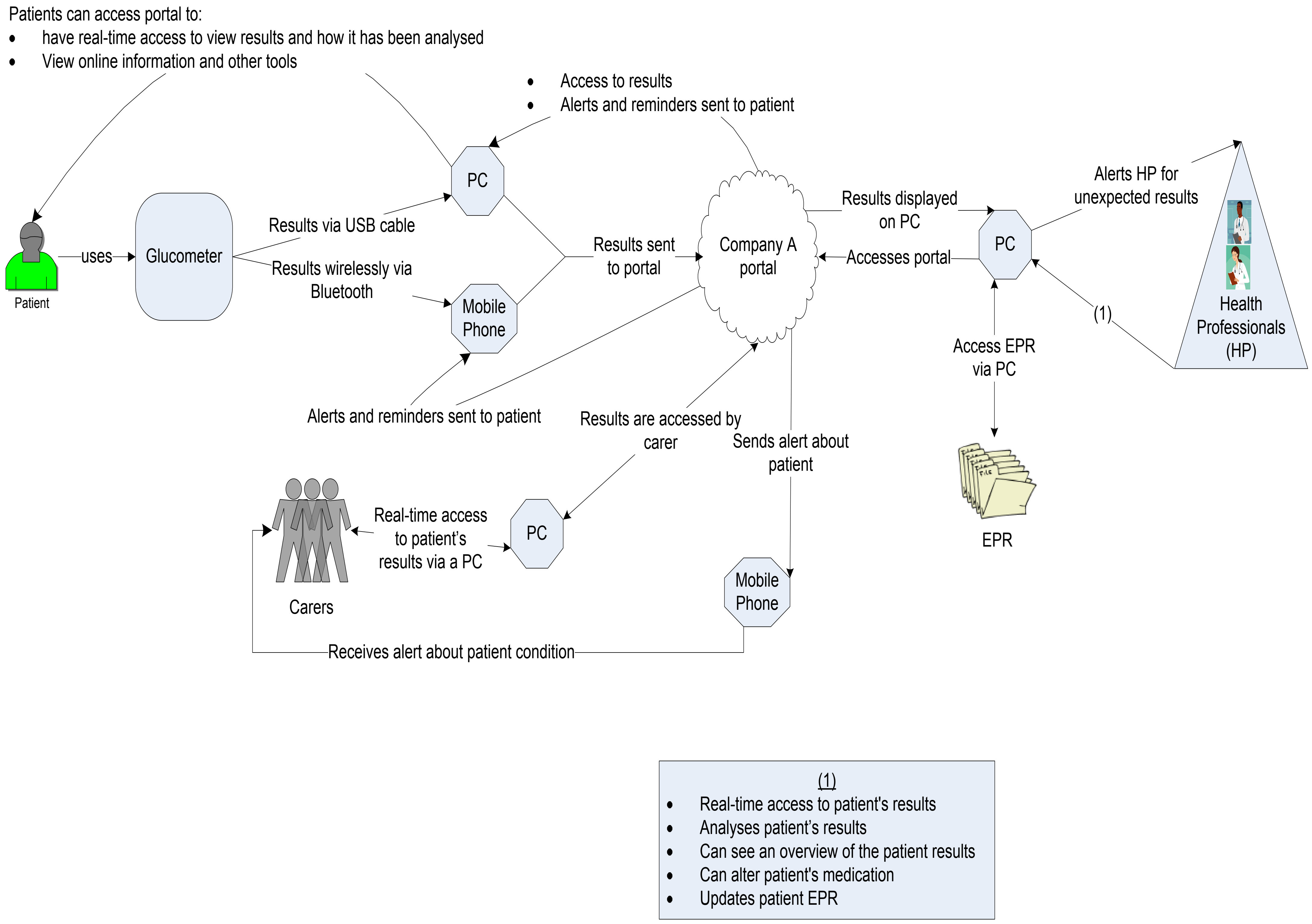
Given the time limitations of the current work, it was decided to assume that for member of staff, the result interpretation takes five minutes. Therefore, the results acquired would have no bias towards any particular way of model organisation.

Interpretation time used in models: 4.00, 5.00 and 6.00 minutes.

4.2 Conceptual DES Models

This section is the description of conceptual model building methodology application into the practice. The DES conceptual model design or building procedures are schematically described in Figure 3.1, it is allocated on page 29 with the description. As mentioned before, in this work, the conceptual model building means to convert data flow diagrams into the DES conceptual model. Therefore, the source data flow diagrams from the publication Adeogun et al. (2011) are also included in this work for clarity.

In this work the entities that go through the DES model of a telehealth system are the patient test results. It is assumed that semantics of the term 'test results' includes any piece of information about patient health condition in a definite period of time. The test results are the set of numbers - measurements results from the POC devices.



Courtesy of Adeogun et al. (2011)

Figure 4.1: Data Flow Diagram for the Offering A

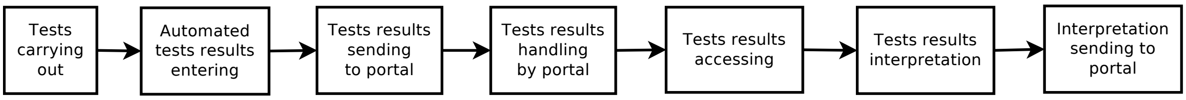


Figure 4.2: Process flow diagram for the Offering A

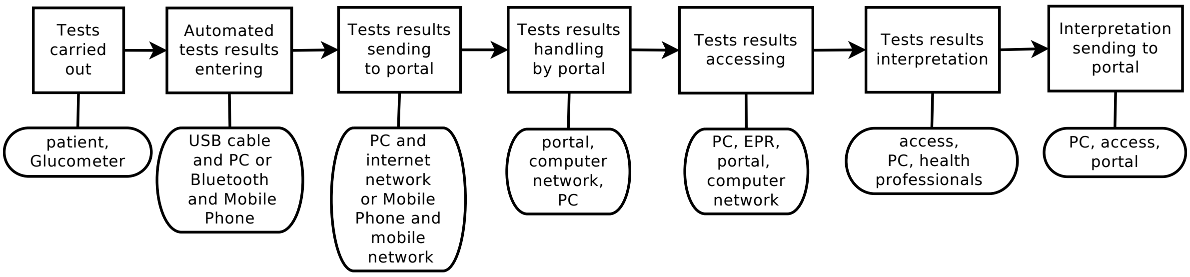


Figure 4.3: Process flow diagram with resources for the Offering A

4.2.1 Offering A

According to conceptual model building flow chart Figure 3.1, the first step of model building is the identification of all the activities that entity meets while on the path, and their order. This information is quite difficult to elect from the Data Flow Diagram for Offering A (Figure 4.1). That is why the publication Adeogun et al. (2011) is useful. This publication provides the convenient division entity processing procedure into separated activities. However, the first flaw was found. There is not enough information about how the entity processing procedure in the whole system finishes. The first assumption that had to be made A.1.22.

The publication Adeogun et al. (2011) describes few processes that occur in the system. To simulate all of them is too complicated, and there is no need to simulate all the processes to achieve the simulation objectives. Therefore, the assumption A.1.1 was made. Then all superfluous processes are excluded from the conceptual model for Offering A.

The result of this conceptual model building step is the Process flow diagram for Offering A Figure 4.2.

The Figure 4.2 represents the activities that entity passes through while on the the path and their order.

Fortunately, the publication Adeogun et al. (2011) provides quite a detailed information about the entity processing procedure in the System A. Therefore, the conceptual model building is started on rather low level of abstraction and the conceptual model for Offering A building process does not contains as many iteration as it could.

Adhering to the Simulation, the next step is to add resources and actors to each activity. This step means to distribute all Figure 4.1 elements between the Figure 4.2 activities. As only tests results processing procedure was left, those not involved in the tests results processing

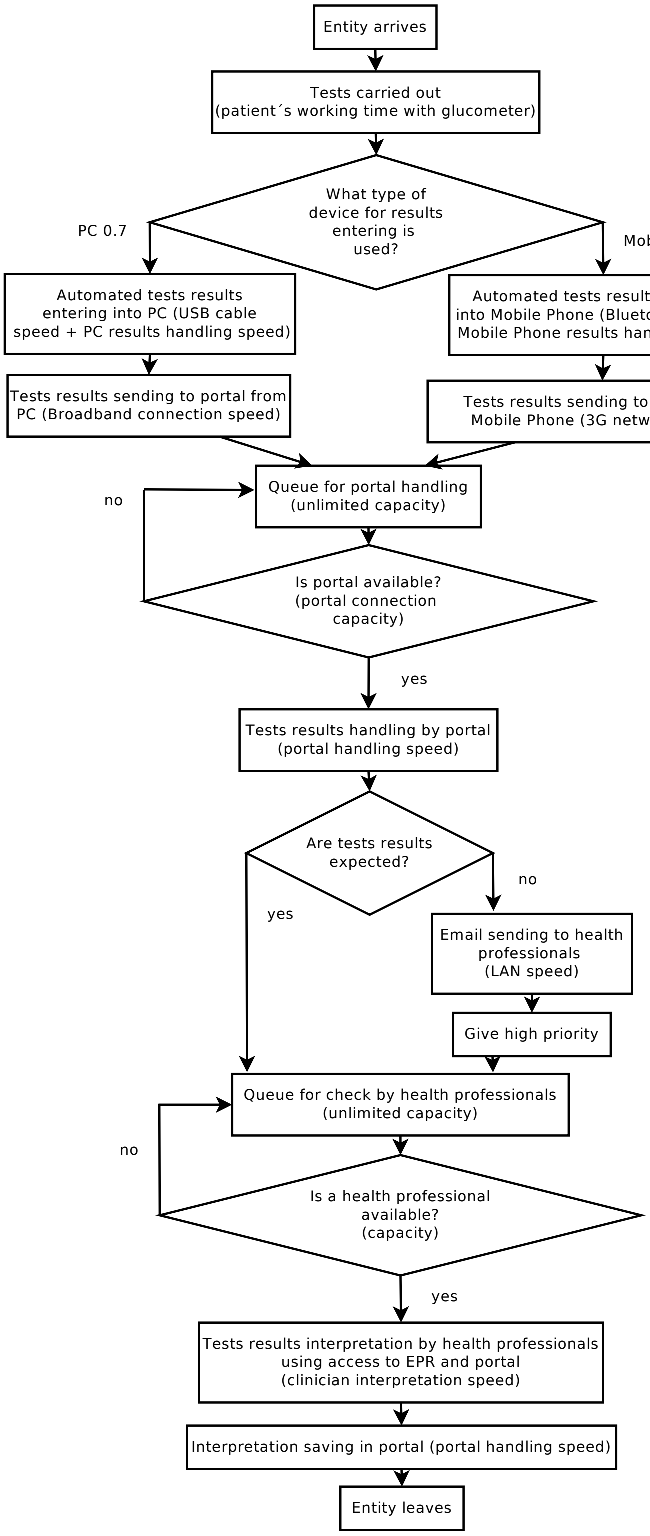


Figure 4.4: Final version of conceptual model for the Offering A

procedure elements of Figure 4.1 have to be excluded. The remaining elements are needed to be distributed between the activities.

A carers role in the system is not described in the publication Adeogun et al. (2011). The carers' influence on entity processing is unknown and it is not clear in what activity carers take part. Therefore the assumption about carers' exclusion from system A.1.2 was made.

The tests results processing procedure starts with the entity creation. It happens when patient is carrying out tests using POC devices. The tests are carried out at patient's location, usually it is patient's house. That is why next assumption needs to be made. The A.1.3 assumption was made. Then the tests carrying out activity speed is limited only by the patient's working time with a glucometer. The queues in this activity do not form. The activity is linear and can be presented by one element in the simulation model.

The next tests results processing procedure activity is the automated tests result entering. This activity involves several sets of resources. The sets differ depending on the device, which is used for automated tests results entering. According to the Data Flow Diagram Figure 4.1, a personal computer or a mobile phone is used for the tests results entering. First of all, the assumption that devices for tests results entering are allocated at patient's location A.1.4 and in conformity with this fact, all resources between POC devices and tests results entering device are also allocated at patient's location. Therefore the queues cannot occur.

As the automated tests results are entering, the assumption A.1.9 activity starts automatically, without delay, then POC devices finish a measurement.

The criteria of Personal Computer (PC) or Mobile Phone (MP) usage is unknown, but their usage expected to be mutually exclusive. Relevant assumptions: A.1.7, A.1.8. The automated entering device choosing is the entity's path branching. The automated tests results entering activity also consists of three elements: automated tests results entering into PC, automated tests results entering into MP, and the entity's path division between these elements. The speed of the automated tests results entering into PC depends on Universal Serial Bus (USB) cable speed, and the tests results processing by PC, but the speed of the automated tests results entering into MP – on Bluetooth speed and tests results processing by MP. As the tests results transfer between the POC devices and tests results entering device, and tests results processing by entering device occur automatically. Thus linearly and sequentially, they are united in one element.

From entering devices the tests results are sent to a portal. There are two kinds of connections used to send the tests results to portal. Connections usage depend on the entering device usage. Therefore, the tests results sending to portal activity are divided into two elements: tests results sending to portal from a PC, and tests results sending to a portal from a MP. The types of connections used for tests result submission to the portal are not specified. Then the assumption A.1.10 is used and the tests results sending to a portal from the PC speed is determined by the Internet (Broadband) connection speed, but tests results sending to portal from MP – by 3G mobile network speed.

The Company A portal is the first system's element, which is a multiuser. Therefore, the portal's throughput is important for the system. As the portal is a common resource, the queue for the portal usage can form and a queue before this activity has to be added. When the entity reaches the portal, the entity processing speed depends only on the portal entity processing speed. The portal performs the primary tests results interpretation and sends alarms to health professionals, if the results are unexpected. The assumption A.1.11 was made. Thus, the tests results handling by the portal activity contains two elements, the actually tests results handling by a portal and a queue before the tests results handling by a portal.

The next Figure's 4.3 activity is tests results accessing. The portal, where the tests results are allocated, and an Electronic Patient Record (EPR) is used in tests results interpretation. To get access to the portal and EPR, a PC and a computer network are used. The access is used to see and update the tests results, and the next assumption A.1.12 is used.

The health professionals carry out the tests results interpretation activity. Health professionals are a common resource, the throughput of tests results interpretation activity depends on the number of health professionals, thus, a queue forms before this activity.

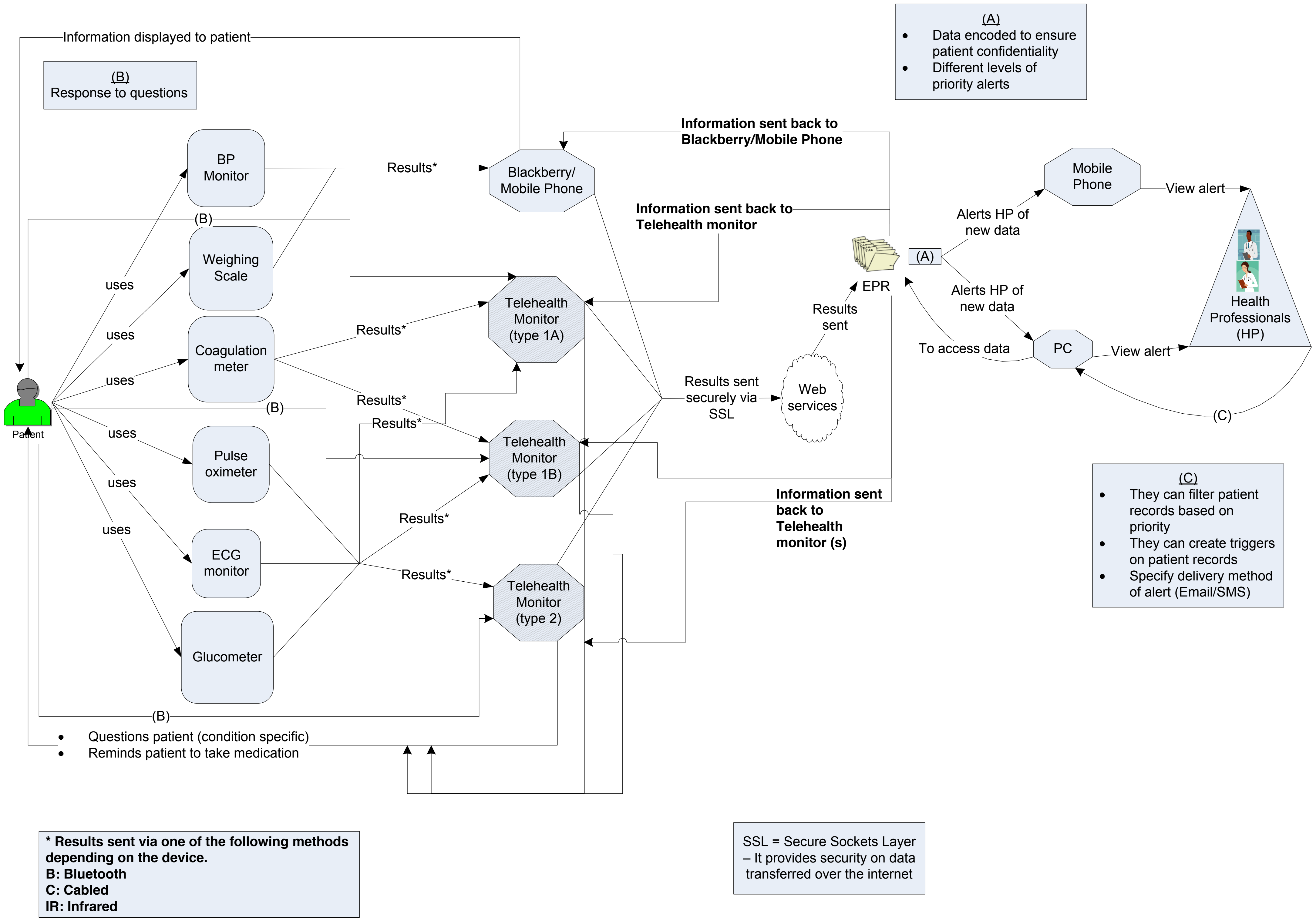
According to Figure 4.1 and Adeogun et al. (2011) health professions receive the alerts about the unexpected tests results. According to assumptions A.1.11 and A.1.13, the unexpected tests results have two more processes than the expected tests results: alert sending and high priority giving. The portal sends alerts to a health professional's PC. The assumption A.1.10 is used. Such tests results separation on expected and unexpected results means the entity's path branch. The frequency of how often the unexpected tests results meet, is unknown. Then the assumption A.1.15 is used.

Every tests results interpretation activity starts then its queue is approached. The assumption about the resources, which are used by health professionals are A.1.17 is used.

The assumption about the tests results interpretation activity end is A.1.12. Thus, the tests results accessing, tests results interpretation and partly the tests results handling by the portal activities as a result, got following elements: the entity's path division into expected and unexpected path branches, a queue for the tests results interpretation and the tests results interpretation by the health professionals activity. The unexpected path branch consists of two elements: a e-mail sending to health professionals and a high priority giving to the unexpected tests results. Expected tests results get to the queue directly, and have a usual priority. The e-mail sending to health professionals element's speed depends on a connection from the portal to a health professional's PC's speed. The assumption A.1.10 is used. The tests results interpretation by the health professional's activity consists of several sub activities and assumption A.1.12 is used.

The assumption A.1.22 requires that the tests results interpretation need to reach a patient. A look at the Figure 4.1 allows to think that a patient's PC can access the Company A portal through the PC to see his or her tests results interpretation. According to this, the tests results interpretation is stored in the portal and can be accessed at any time. Therefore, the interpretation saving in portal activity speed is limited only by the portal saving speed.

The result of the DES conceptual model design or the building procedure for Offering A is the Figure 4.4 Final version of conceptual model for the Offering A.



Courtesy of Adeogun et al. (2011)

Figure 4.5: Data Flow Diagram for the Offering B

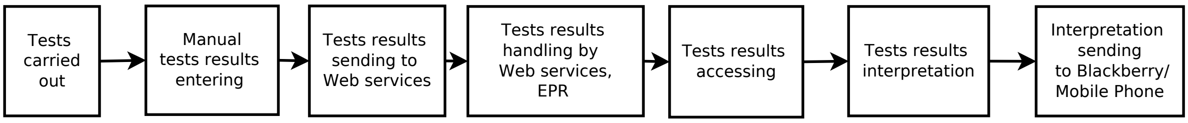


Figure 4.6: Process flow diagram for the Offering B

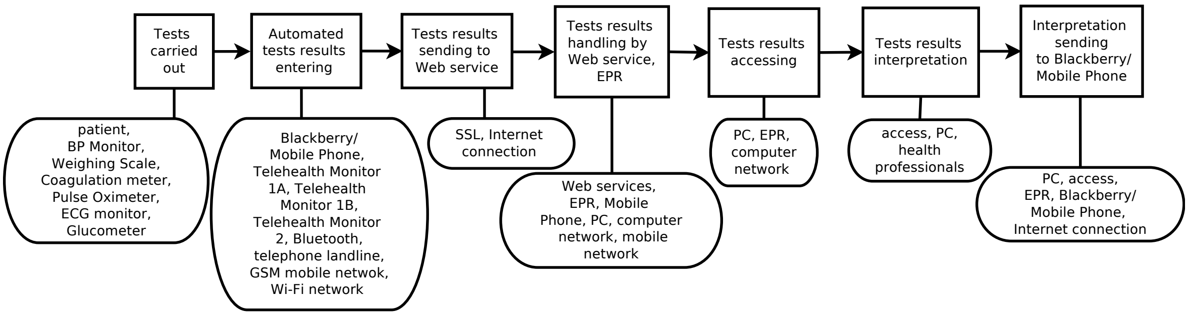


Figure 4.7: Process flow diagram with resources for the Offering B

4.2.2 Offering B

As mentioned previously, DES conceptual model design or building starts with the process flow diagram building. Using Figure 4.5, publication Adeogun et al. (2011) and relevant assumptions: A.1.22 and A.1.1, the basic entity or tests results processing activities were defined. The Figure 4.6 represents the activities, and together they form the tests results processing in the system.

The next step of the DES conceptual model building Figure 3.1 is each activity resources and actors adding. After the Figure 4.5 elements distribution between Figure 4.6 activities, the Process flow diagram with resources for the Offering B Figure 4.7 was received.

The publication Adeogun et al. (2011) and Figure 4.5 confirm that Offering B is the system for several chronic conditions, that is why it consists so many POC devices, and every patient do not use the all POC devices. In this case, the A.1.18 is used. This activity gives the entity path branch. The number of branches depends on the number of chronic conditions monitored by Offering B. The path choosing criteria for the chronic conditions was not provided. Therefore, the assumption A.1.19 is relevant here. Also assumption A.1.3 is relevant for corresponding to tests carrying out activity conceptual model's elements. The tests carrying out activity gave the four path branches as the amount of monitored chronic conditions by Offering B.

After the tests are carried out, the automated tests results entering activity follows. The several assumptions are relevant for this activity: A.1.4, A.1.9 and A.1.7. The several devices can be used for tests results entering. As the assumption A.1.7 is used, the path branch need to be created for the automated tests results entering. The connections and networks used for

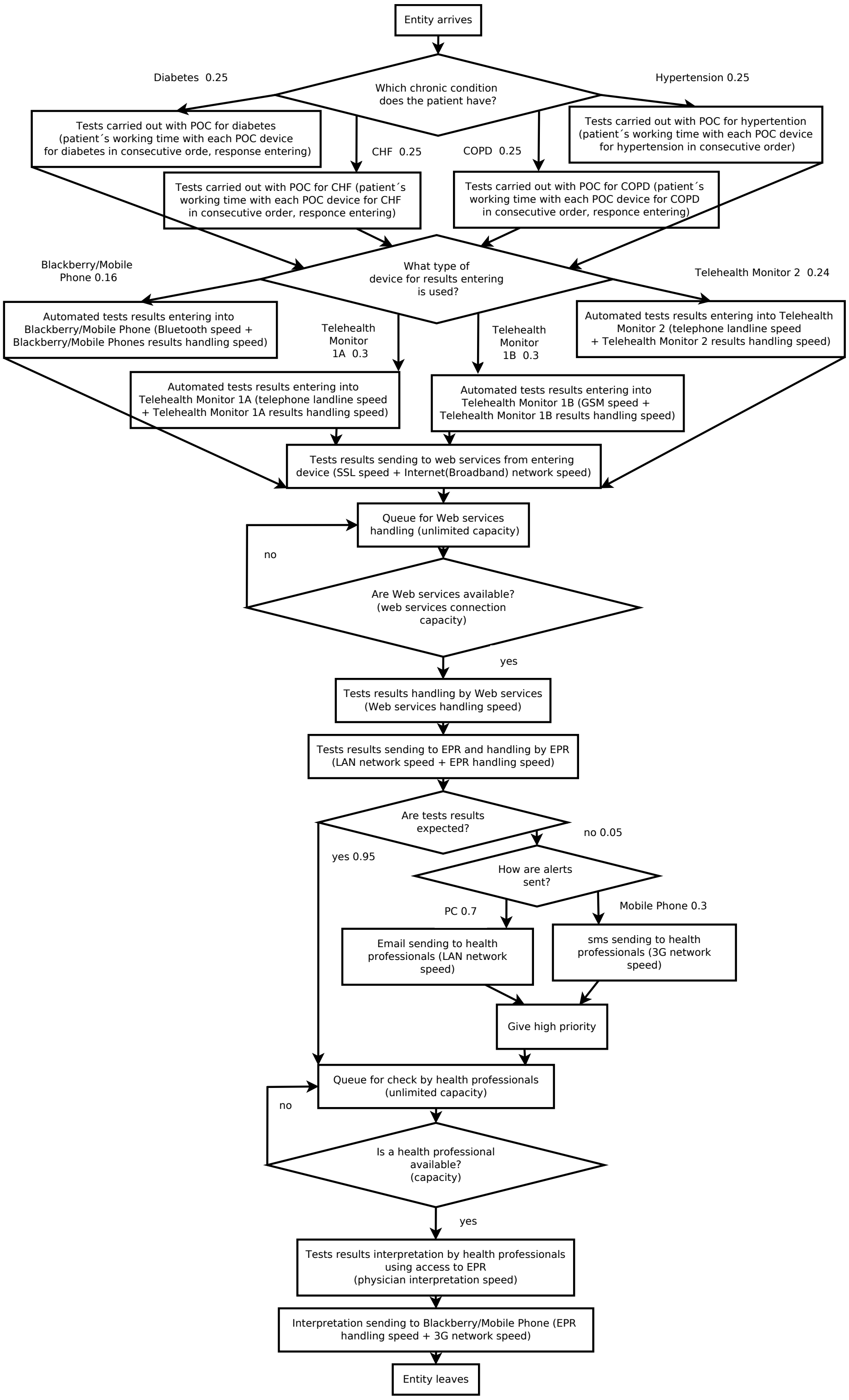


Figure 4.8: Final version of conceptual model for the Offering B

tests results transfer from the POC devices to entering devices, depends on a used entering device. The usage of a type of entering device is connected with the POC devices used to monitor chronic conditions. Thus the assumption A.1.20 is used. As the results of conceptual model building from this activity, the entity path division into four branches, and four on the number of entering devices, and four automated tests results entering elements were found. Each element's speed is limited according to the entering device's entity handling speed and corresponding connection or network speed.

From the entering devices, the tests results or entity is sent to a web service. The Secure Sockets Layer (SSL) Onyszko (2002) over an unknown connection is used. Of course, the most likely, given connection has access to the Internet. The tests results are sent via SSL from all the entering devices. This activity occurs automatically and is represented with one element in conceptual model. The speed of this element depends on the SSL and the Internet speed.

The tests results handling by the Web services, EPR activity passes in two stages: tests results handling by Web services and then tests results handling by the EPR. The Web services are the first common element. The throughput of the Web services is limited so the tests results handling by the Web services stage gives two models elements – tests results handling by the Web services and a queue before tests results handling by the Web services.

The tests results have to be added to EPR. EPR is connected to the Web services and the health professionals but the number of connections to the EPR is much smaller than the Web services can have, therefore the throughput of EPR can be excluded. EPR saves not only the arrived tests results but also checks if it expected or not. If the entity is unexpected, EPR would send the alerts to the health professionals. The assumption A.1.11 is used and tests results handling by EPR is represented bya one element with the same name, the speed of this element is limited by the tests results handling speed by the EPR.

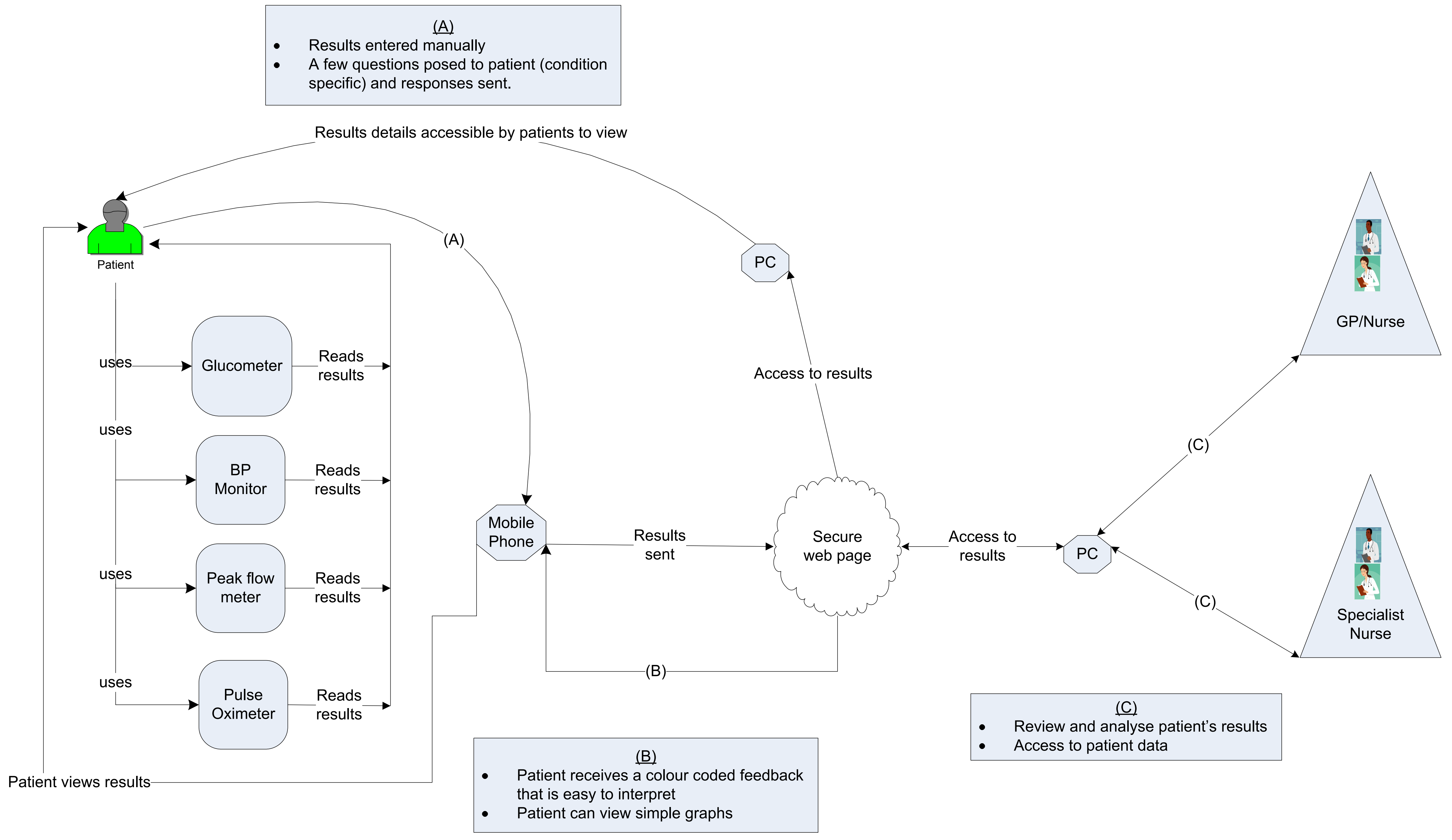
The next Figure's 4.7 activity is the the tests results accessing. The assumption A.1.12 is used.

The further entity processing activity is an interpretation by the health professionals. The health professionals are the common resource, the number of health professionals defines the throughput of tests results interpretation by the health professionals' activity, thus, a queue need to be included before this activity. The assumptions A.1.11, A.1.13, A.1.14, A.1.15 and A.1.8 are used to make the alerts sending process clear. The unexpected results require the complementary elements of a Conceptual model for Offering B: entity's path branch for the alerts sending device, the two elements of alert sending – via a PC and via a MP and a high priority is given. The alert sending via PC speed depends on Local Area Network (LAN) speed, but the alert sending via MP – 3G network speed. The assumption A.1.10 proves it.

According to the assumption A.1.17, each health professional has the resources for tests results interpretation. The entity's interpretation by the health professionals consists few in–built activities, A.1.12 but the speed of interpretation by the health professionals' activity is defined by a physician's interpretation speed.

As specified in the assumption A.1.22, the tests results interpretation need to be provided to the patient. The Figure 4.5 shows that information is sent from the EPR to the patient's Blackberry/Mobile Phone (MP), as only a Blackberry/MP displays information to the patient. From this and assumption A.1.12, it follows that the interpretation passes the EPR saving, Telehealth Monitor Message (TMM) making and the Internet connection, thus the speed of all these processes defines the speed of the interpretation sending to a Blackberry/MP.

The DES conceptual model for Offering B is the Figure Final version of conceptual model for the Offering B.



Courtesy of Adeogun et al. (2011)

Figure 4.9: Data Flow Diagram for the Offering C

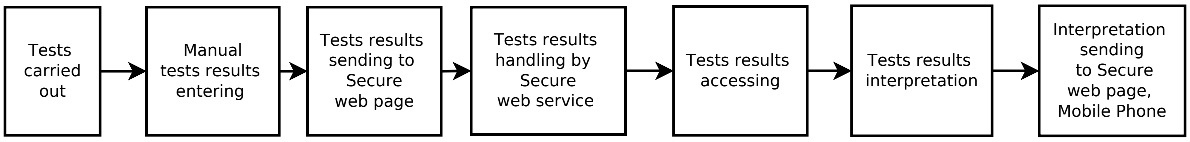


Figure 4.10: Process flow diagram for the Offering C

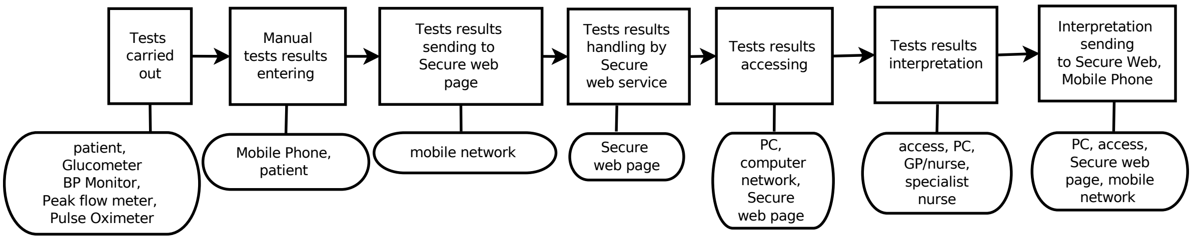


Figure 4.11: Process flow diagram with resources for the Offering C

4.2.3 Offering C

The conceptual model building flow chart Figure 3.1 provides a process flow diagram building as the first step. From the Data Flow Diagram for the Offering C 4.9 and publication Adeogun et al. (2011), the basic activities of the entity or tests results processing were allocated. Used assumptions are A.1.22 and A.1.1. The acquired Process flow diagram for the Offering C is the Figure 4.10

The second step of the DES conceptual model building is the definition of the resources and actors of each activity. Using 4.9, all elements were distributed between 4.10 activities of the Process flow diagram with resources for the Offering C (Figure 4.11) is result of the conceptual model building's second step.

According to the publication Adeogun et al. (2011) and Figure 4.9, the Offering C is the system for several chronic conditions monitoring. Relevant assumptions A.1.18, A.1.19 and A.1.3 were used. The tests carrying activity gives the four entity-path branches equal to the number of monitored chronic conditions by Offering C. All these path's branches consist on a set of POC devices, used for the monitoring correspond condition.

As in Offering C, the manual tests results entering activity are used, a patient enters the tests results and response into the entering device. The assumption A.1.4 is used. The MP is entering the device in Offering C. The manual tests results activity gives the only one DES conceptual model element – manual tests results and response entering into a MP. The speed of this activity is defined by the patient's working time with MP and MP's results handling speed.

From MP tests results are transmitted to secure web page. The transfer connection or network is unknown and thus the assumptions A.1.9 and A.1.10 are relevant. This activity is represented by one element: tests results sending to a secure web page from a MP. The speed

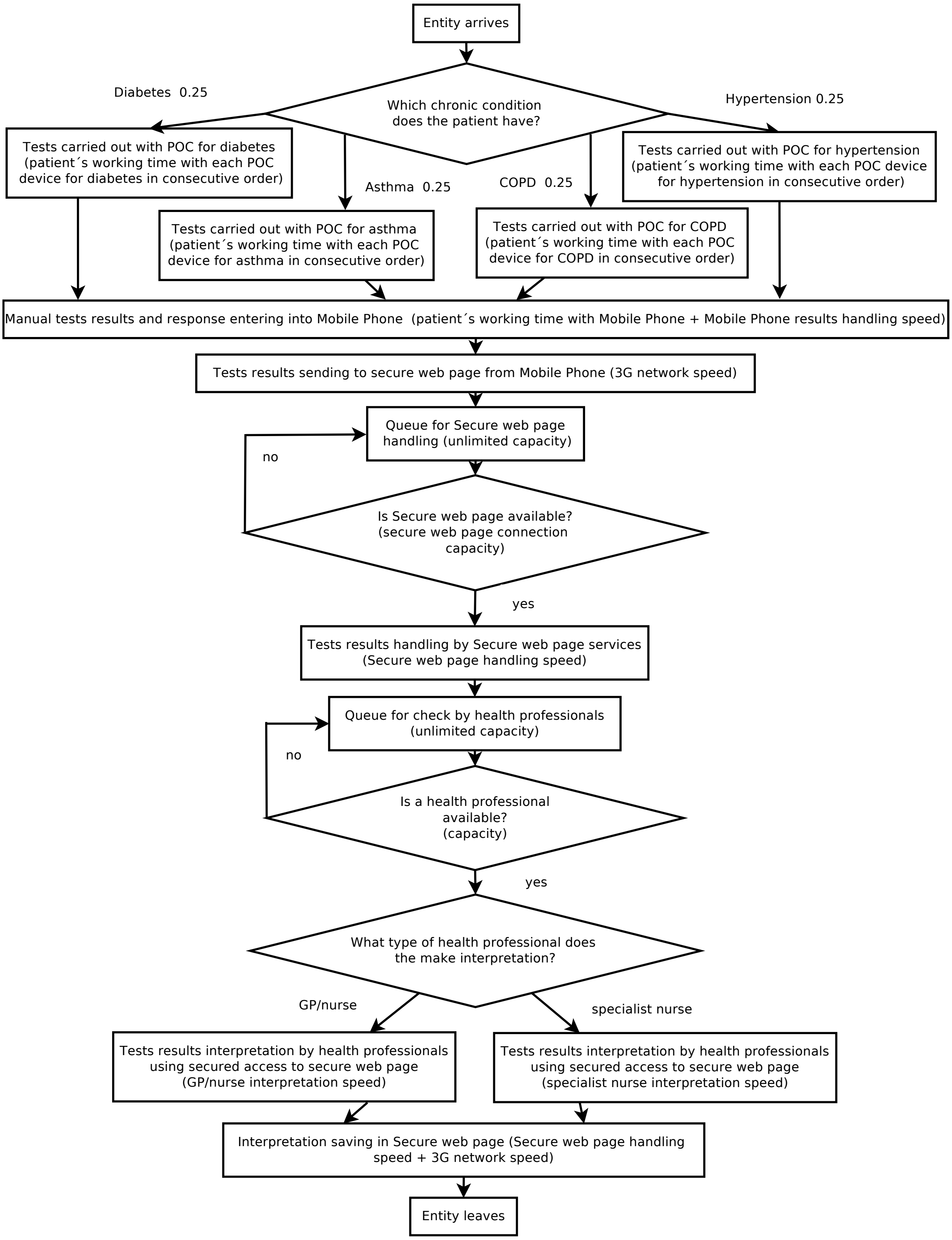


Figure 4.12: Final version of conceptual model for the Offering C

of this element depends on a 3G network transmission speed.

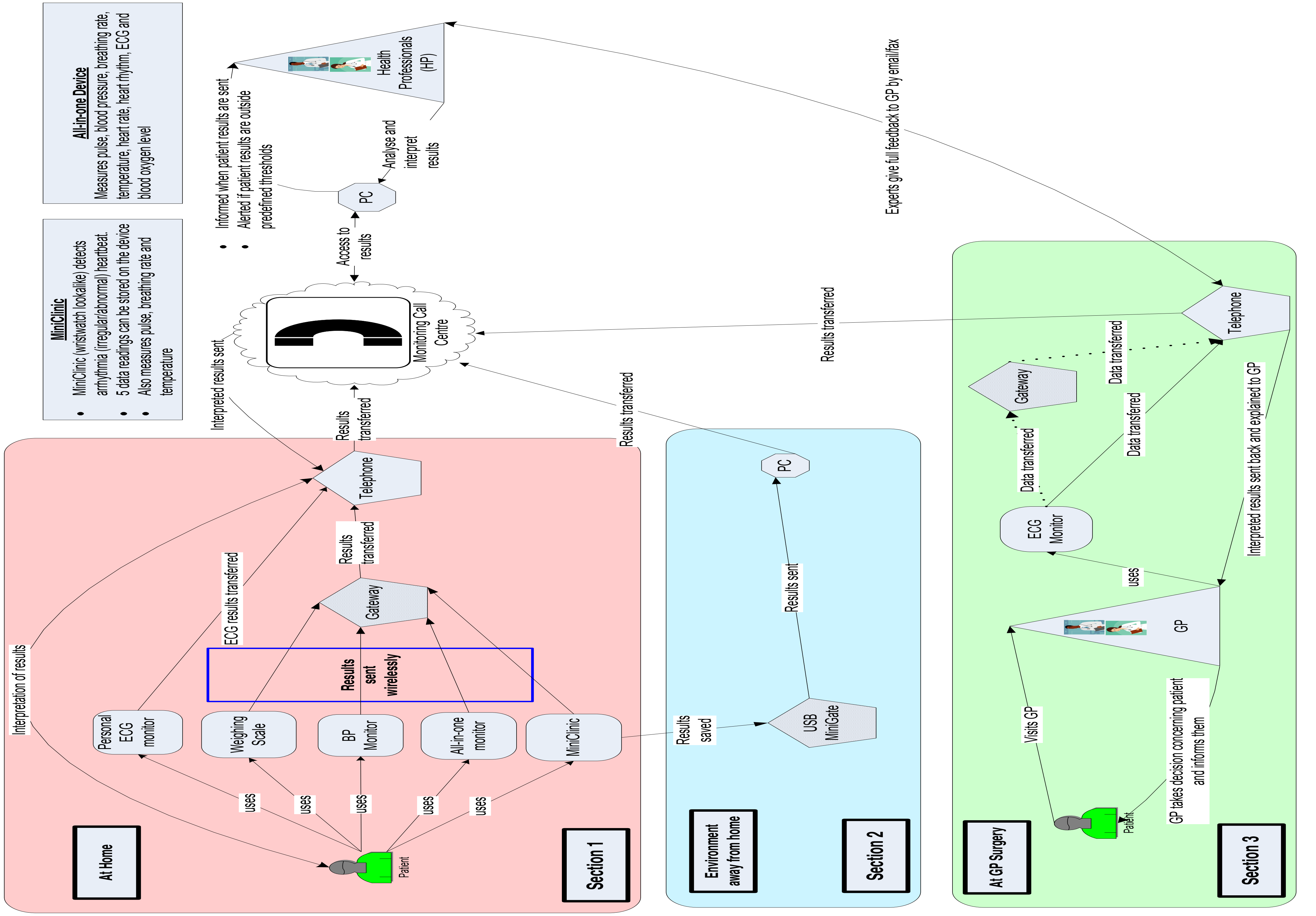
The secure web page receives tests results of all the monitored patients. Therefore, the throughput of secure web page is important for Offering C to work and queue before the tests results handling by a secure web page can form. The tests results' handling by the secure web page services' speed is limited by the secure web page handling speed.

As the assumption A.1.12 is used, the tests results accessing activity is excluded from the conceptual model.

The next entity processing activity is an interpretation by the health professionals. Health professionals are a common resource, thus, a queue needs to be included before this activity. There are two types of health professionals in the Offering C. Not all types of health professionals are connected with each other, and the criteria for the usege of a particulat health professionals' type is unknown. Because of that, it was decided to create a single queue for all types of health professionals. Each newly arriving test result is processed on the 'first–come, first–served' basis. Allocating first health professional that became available. The assumptions A.1.17 and A.1.12 are relevant for this activity. The tests results interpretation gives three elements: queue, tests results interpretation by GP/nurse, and the tests results interpretation by a specialist nurse.

As the assumption A.1.22 requires to make a tests results interpretation available to a patient, the Figure 4.9 leads to a thought that tests results interpretation is saved in a secure web page where is it available to a patient through the PC, and is sent to patient's MP. The assumption A.1.12 explains that the tests results interpretation activity speed consists from a secure web page handling speed and 3G network speed.

The result of Figure 3.1 applying for the Offering C is the DES conceptual model for Offering C Figure 4.12.



Courtesy of Adeogun et al. (2011)

Figure 4.13: Data Flow Diagram for the Offering D

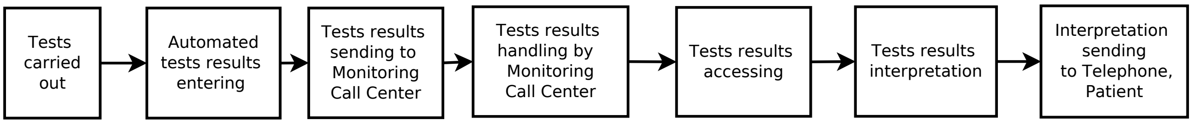


Figure 4.14: Process flow diagram for the Offering D

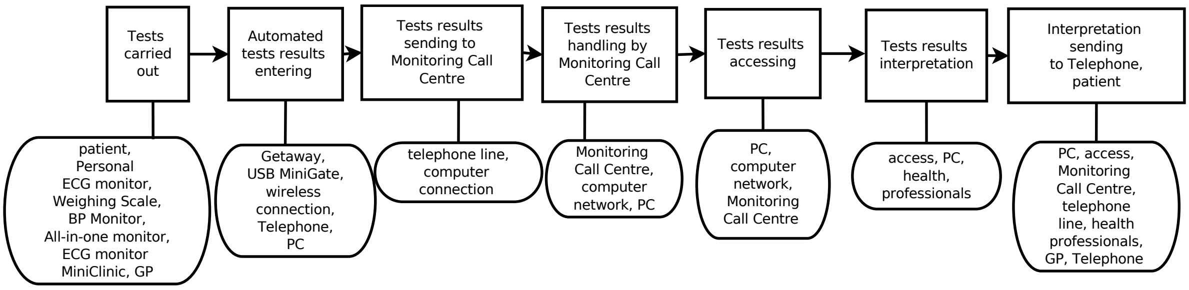


Figure 4.15: Process flow diagram with resources for the Offering D

4.2.4 Offering D

According to the building procedure Figure 3.1, DES conceptual model design or building starts with a Process Flow diagram building. Using Figure 4.13, publication Adeogun et al. (2011) and relevant assumptions: A.1.22 and A.1.1, the basic entity or tests results processing activities were defined and represented in Figure 4.6.

The next step of the DES conceptual model building is the resources and actors adding to each activity. After the Figure 4.13 elements distribution between Figure 4.14 activities, the Process flow diagram with resources for the Offering D Figure 4.15 was constructed.

The Process flow diagram with resources for the Offering D Figure 4.13 confirms that Offering D provides three cases of patients' location. Patients can carry out the tests at home, out of home and at GP surgery. These three cases give three path branches and the probabilities of each branch need to be defined. The case of patients carry out tests away from home happens with a 40% probability. Because such high probability, it was assumed that carrying out tests using one POC device away from home is a great opportunity to patients to live active social live, so patients are using this opportunity. The other case is the tests carrying out by GP. Although this approach does not allow using all the telehealth system advantages, it can be very useful. The rare carrying out tests by professional can has a nature of an obligatory check. The probability of tests carrying out by GP is assumed to be 10%. The third case does not strongly differ from the tests carrying activity in the Offering B. The assumptions A.1.18, A.1.19 and A.1.3 are relevant also for this activity. This third case of activity is converted similarly to carrying out activity in the Offering B. The difference is that probabilities of respiratory and cardiac diseases is more significant than of Congestive heart failure (CHF) and

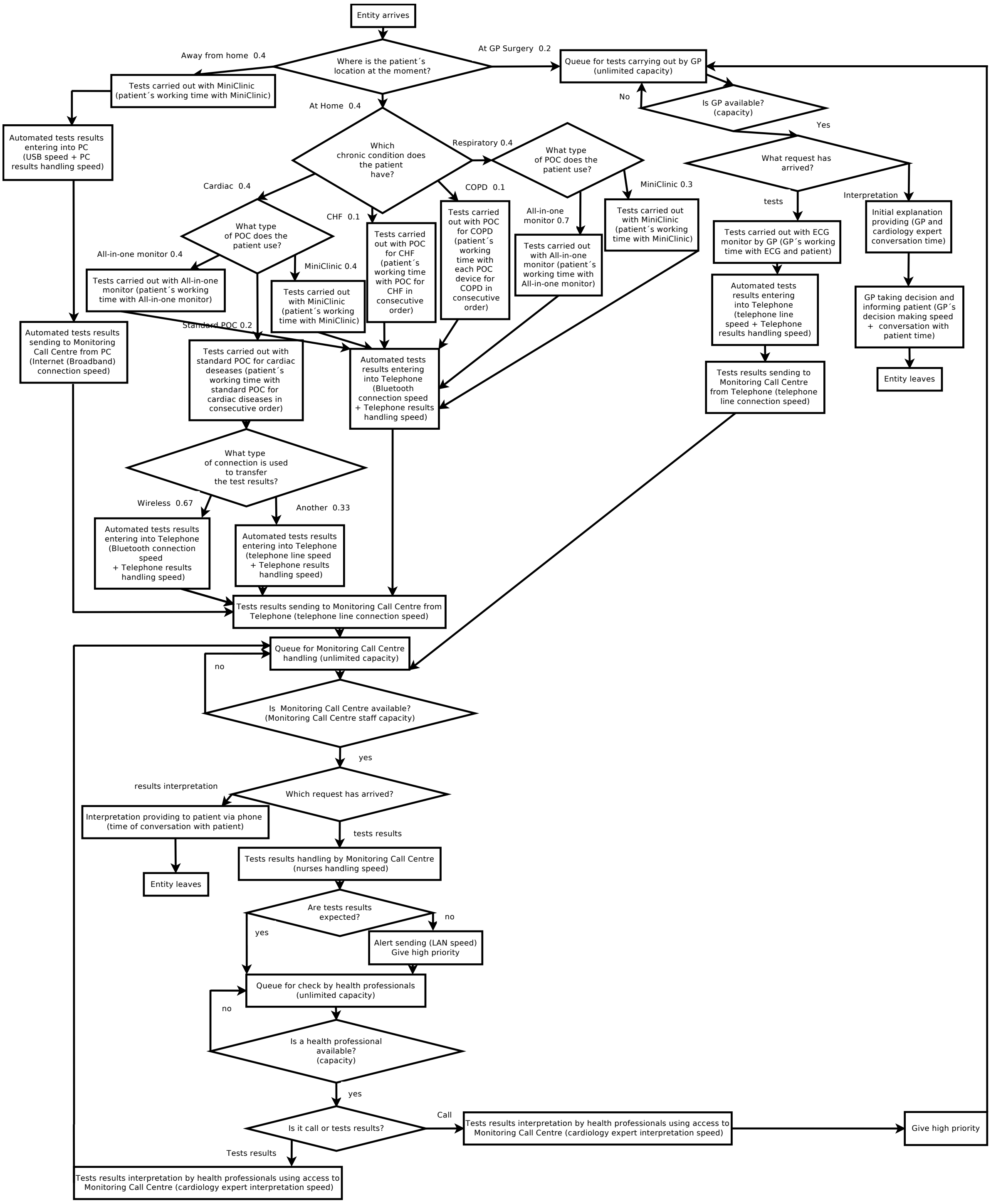


Figure 4.16: Final version of conceptual model for the Offering D

Chronic obstructive pulmonary disease (COPD) because the respiratory and cardiac diseases can consist several deceases. The probabilities of CHF and COPD are 10%, while probabilities for respiratory and cardiac are 40%. Another difference is the two multi–task POC devices. The usage of only one of them can be enough to monitor several conditions, therefore, the standard POC devices are suitable only for the cardiac diseases and a small probability of usage was appropriated to them by 20%. The remaining probability is regularly distributed between the multi task POC devices.

The automated tests results entering activity follows the tests carrying out. The several assumptions are relevant for this activity: A.1.4, A.1.9 and A.1.7, A.1.10. Several devices can be used for tests results entering. That activity depends on the cases and each case is converted separately using an assumptions and the Offering B example. The assumption has to be made for the tests results transmissions to telephone, the telephone line is used as the most appropriate. The Bluetooth was already used as a wireless connection in the Offering A, and will be used as a wireless connection in the Offering D.

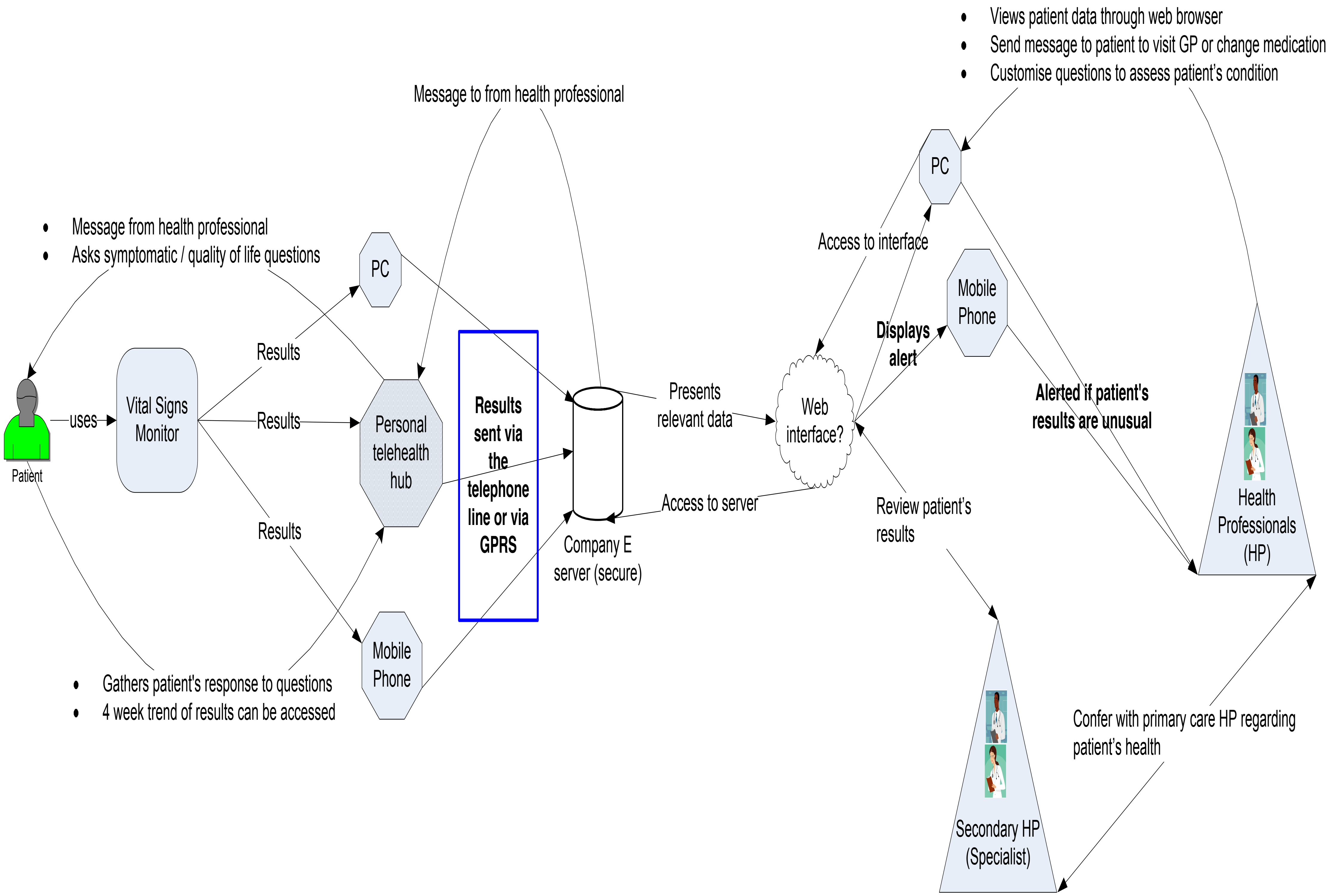
The first common resource on a pathway is the Monitoring Call Centre (MCC), which is a human–assisted (non–automatic) service. The nurses perform the primary tests results handling and send the alerts to health professionals. Assumptions A.1.11, A.1.17, A.1.12 A.1.15 are used for this activity conversion.

The alerts sending activity conversion is made similarly to the Offering A. A.1.15, A.1.10 and A.1.13 are relevant assumptions.

The health professionals interpretation activity is similar to previous Offerings and is converted the similarly. The assumptions A.1.17 and A.1.12 need to be used for this activity conversion.

The next activity has two branches, further path depends on the type of tests results: tests results from GP surgery requires the feedback giving to GP by phone. The health professionals call to GP and to such calls the high priority is given. The GP receives a feedback via telephone, takes the decision and informs the patient. Other tests results interpretations are sent to acMCC. Monitoring a call, staff provides tests results interpretation to the patients via phone.

The final DES conceptual model for Offering D is represented by Final version of conceptual model for the Offering D Figure 4.16.



Courtesy of Adeogun et al. (2011)

Figure 4.17: Data Flow Diagram for the Offering E

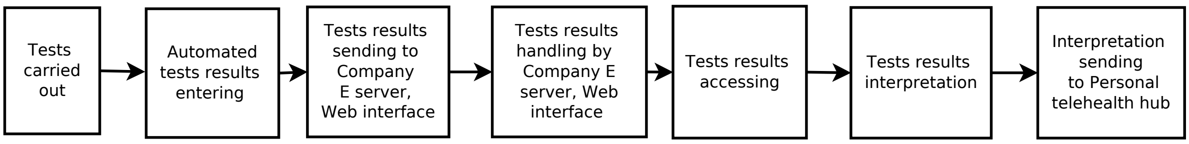


Figure 4.18: Process flow diagram for the Offering E

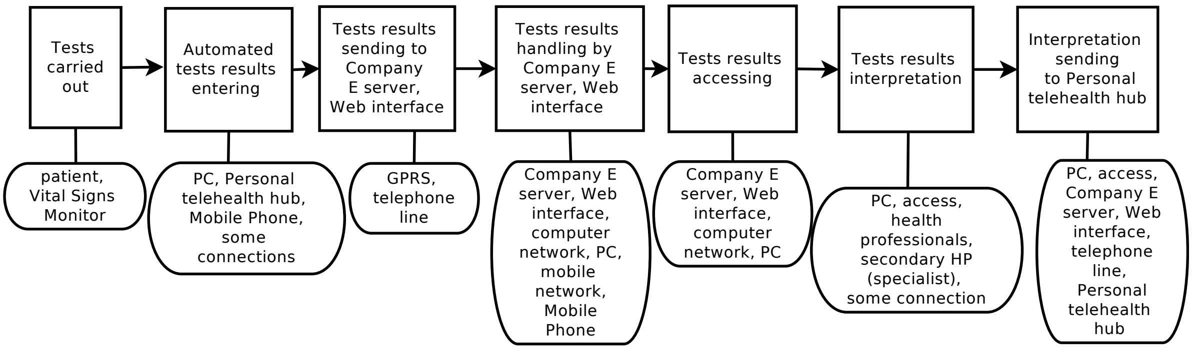


Figure 4.19: Process flow diagram with resources for the Offering E

4.2.5 Offering E

The conceptual model design procedure section 3.1 requires starting with the basic entity or tests results processing activities definition. Using Data Flow Diagram for the Offering E Figure 4.17, publication Adeogun et al. (2011) and assumptions A.1.22, A.1.1 the Process flow diagram for the Offering E was created and presented by Figure 4.18

The next step of the DES conceptual model design or building is the addition of resources and actors to each activity from Figure 4.18. For each element of Figure 4.17 a corresponding activity needs to be found. The result of this step is the Process flow diagram with resources for the Offering E Figure 4.19.

The publication Adeogun et al. (2011) confirms that Offering E manages and prevents several conditions. But as for all the chronic conditions the same POC device is used, therefore, A.1.3 assumption has to be used, and the tests carrying out activity gives two elements of conceptual model, the speed of tests carrying out element gathers from patient's working time with Vital Signs Monitor (VSM) and patient's response entering.

In case of automated tests results, three entering devices are involved to the entering activity. The relevant assumptions here are A.1.4, A.1.9 and A.1.20. Thus the automated tests results entering activity need to be represented by the three conceptual model elements: automated tests results entering to MP, automated tests results entering to PC, and automated tests results entering to personal telehealth hub. The assumption A.1.10 has to be used in this case. As personal telehealth hub is a small device which is similar to MP, the assumption's A.1.10

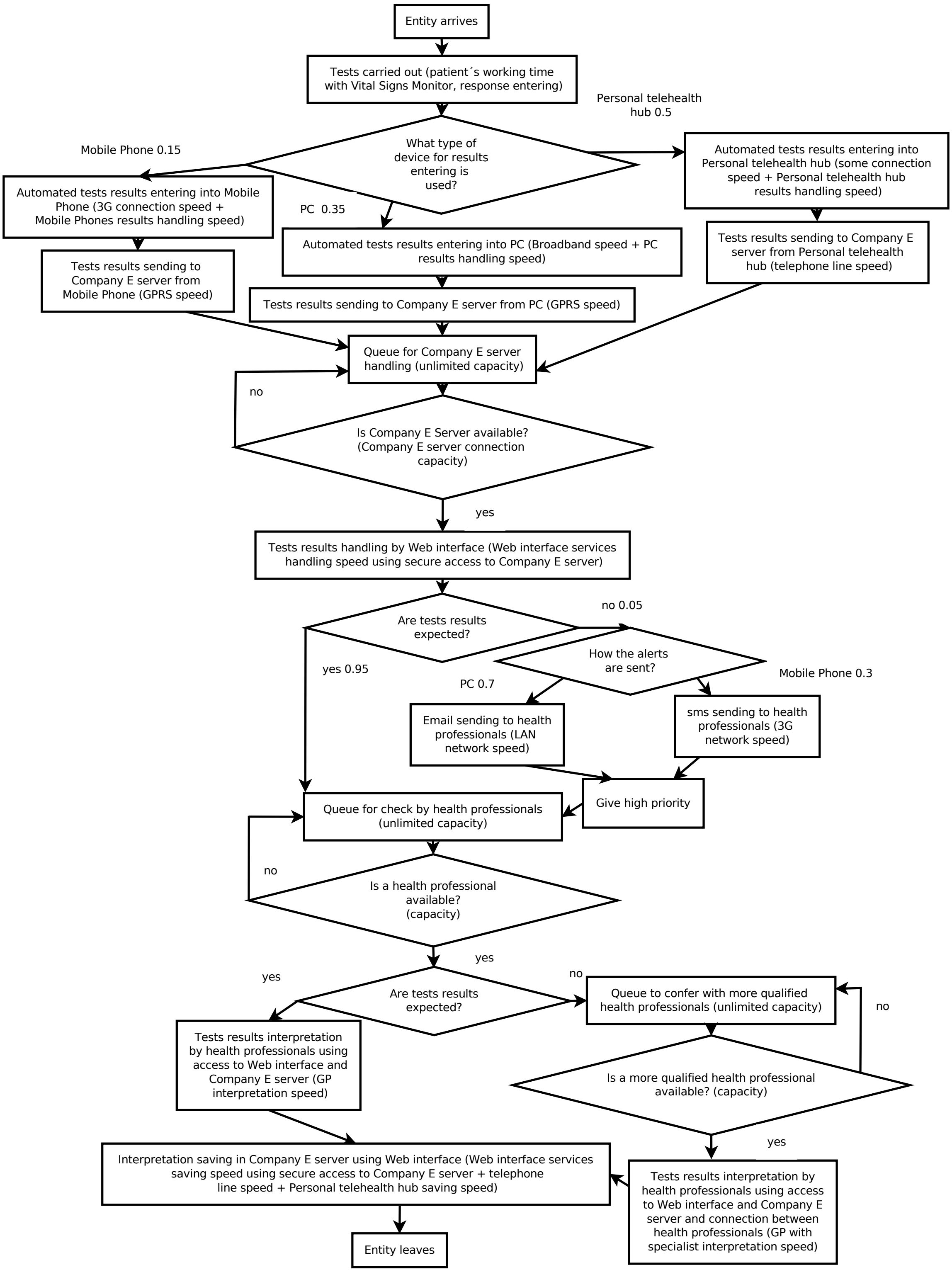


Figure 4.20: Final version of conceptual model for the Offering E

part for MP is relevant for personal telehealth hub. The speed of the automated tests results entering to MP is 3G speed and MP results handling speed, speed of the automated tests results entering in PC – Broadband speed and the PC results handling speed, speed of the automated tests results entering to personal telehealth hub – 3G speed and personal telehealth hub results handling speed.

The tests results are transferred using two types of connections: telephone line and General Packet Radio Services (GPRS). The telephone line transfers the entities from personal telehealth hub Adeogun et al. (2011), thus, GPRS transfer entities from PC and MP. Therefore, the tests results sending to Company E server, a Web interface activity gives three elements: one to each correspond automated tests results entering elements. Tests results sending to Company E server from a PC and tests results sending to a Company E server from MP have the speed equal to GPRS tests results sending speed, but speed tests results sending to Company E server from personal telehealth hub – to telephone line speed.

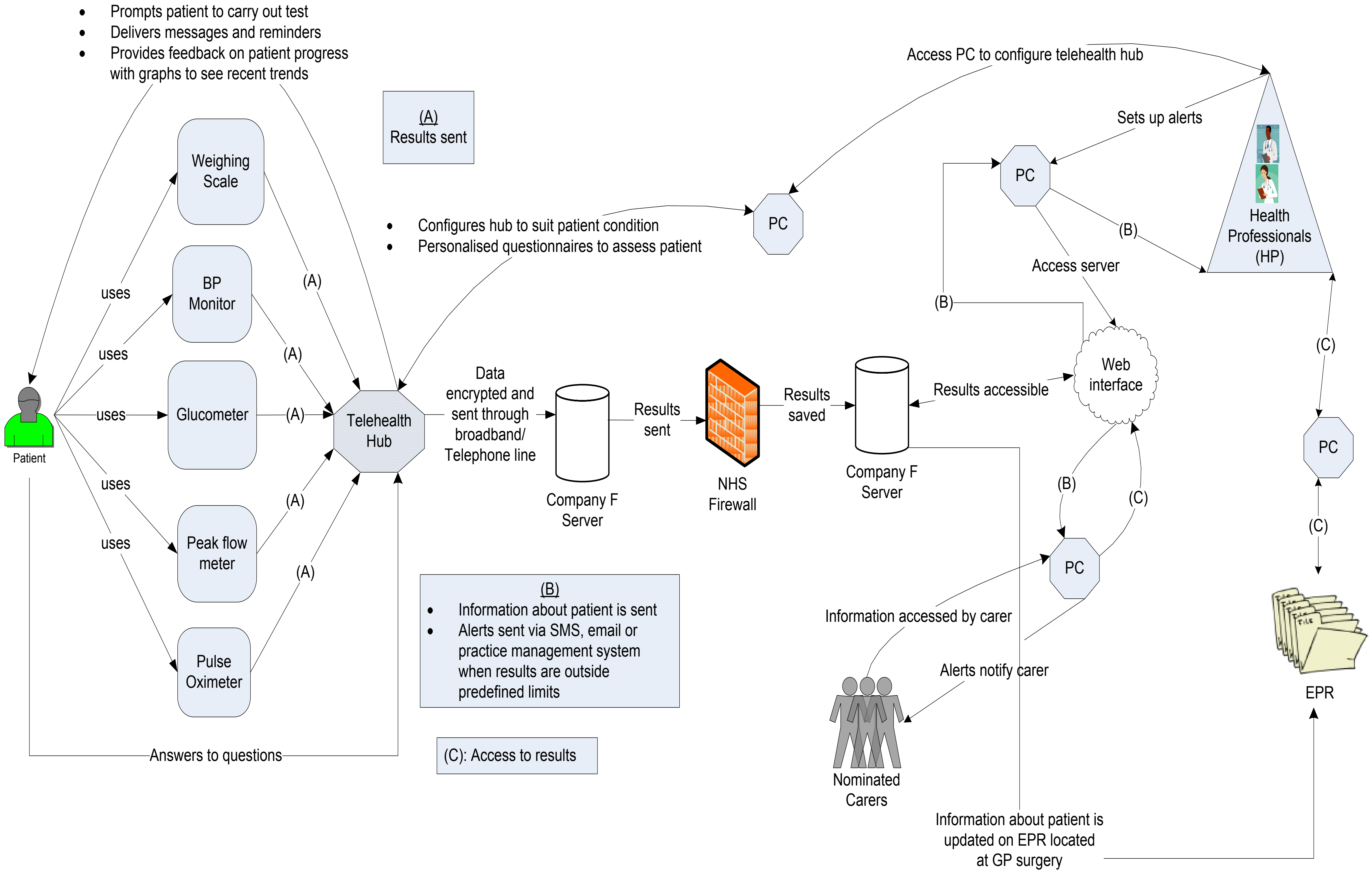
As Company E server is accessible through a Web browser Adeogun et al. (2011), a Web interface provides such function Figure 4.17. That is why the tests results handling is performed by a Web interface. The queue element has to be added before the Web interface because Web interface receives entities from every patient. The tests results' handling by the Web interface speed is defined by the Web interface services' handling speed using a secure access to Company E server.

For the next activity, relevant assumptions are A.1.11, A.1.13, A.1.14, A.1.10 A.1.15 and A.1.8. Therefore, the entity path is divided into path for the expected and unexpected tests results. Expected results go directly to queue but unexpected has two alerts sending elements and the path division between them, a high priority is given and then unexpected tests results get in a queue. This part of activity is similar to Offering B and is converted into similar elements as in the Offering B.

The Offering E contains two types of health professionals – GPs (primary) and the specialists (secondary) Adeogun et al. (2011). The GPs and specialists confer with each other, but the cases and frequency of consultations are unknown. Assumption A.1.21 is used to make clear the tests results interpretation passing. Also assumption A.1.12 is relevant to this activity. Therefore, the interpretation is divided into interpretation of the expected and unexpected results. Expected results require only a GP but unexpected – a GP and a specialist.

The final activity is tests results interpretation storing in Company E server using the Web interface. Assumptions A.1.22, A.1.12 are relevant for the final activity. The speed of this activity consist the Web interface services storage Input/Output (I/O) speed using a secure access to Company E server, telephone line speed and personal telehealth hub storage I/O speed.

The final DES conceptual model for Offering E is represented by Figure 4.20.



Courtesy of Adeogun et al. (2011)

Figure 4.21: Data Flow Diagram for the Offering F

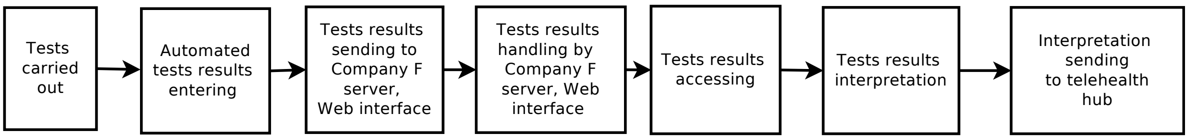


Figure 4.22: Process flow diagram for the Offering F

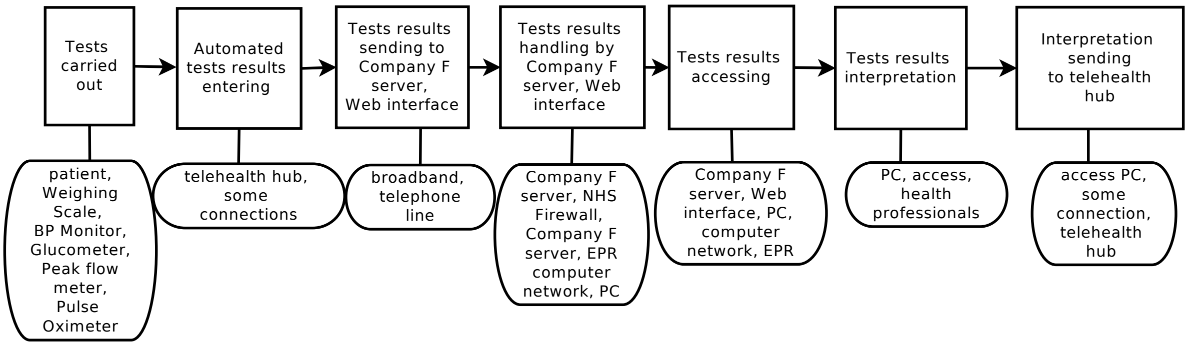


Figure 4.23: Process flow diagram with resources for the Offering F

4.2.6 Offering F

The first step of the conceptual model building is a process flow diagram building. Using the Data Flow Diagram for the Offering F Figure 4.21, publication Adeogun et al. (2011) and assumptions A.1.22, A.1.1 the Process flow diagram for the Offering F for Offering F, was created and presented by Figure 4.22

On the next step of the DES conceptual model design or building, an assumption A.1.2 is used. The Process flow diagram with resources for the Offering F for Offering F is Figure 4.23.

The tests carrying out activity was converted similarly to Offering C. Assumptions A.1.18, A.1.19 and A.1.3 are used.

In automated tests results entering activity was converted as in the Offering C. The relevant assumption is A.1.4. However, as it is an automated tests results activity, the transferring to entering device has to be included. The Offering F as Offering E consists telehealth hub and the automated tests results entering activity will be converted similarly to the Offering E, the difference is that Offering F uses only one type of entering device. The assumption A.1.10 was used and 3F connection speed was included into the automated tests results entering activity.

The tests results are transferred using a Broadband connection, and the tests results sending activity is converted as in the Offering B.

A Company F server is the first common resource in the system and was converted as in the previous systems. The next Company F server usage Web interface is the same as in the Offering E and is converted as in the Offering F. After a Company F server entity reaches EPR. In addition, this element is included into a conceptual model. According the assumption A.1.10

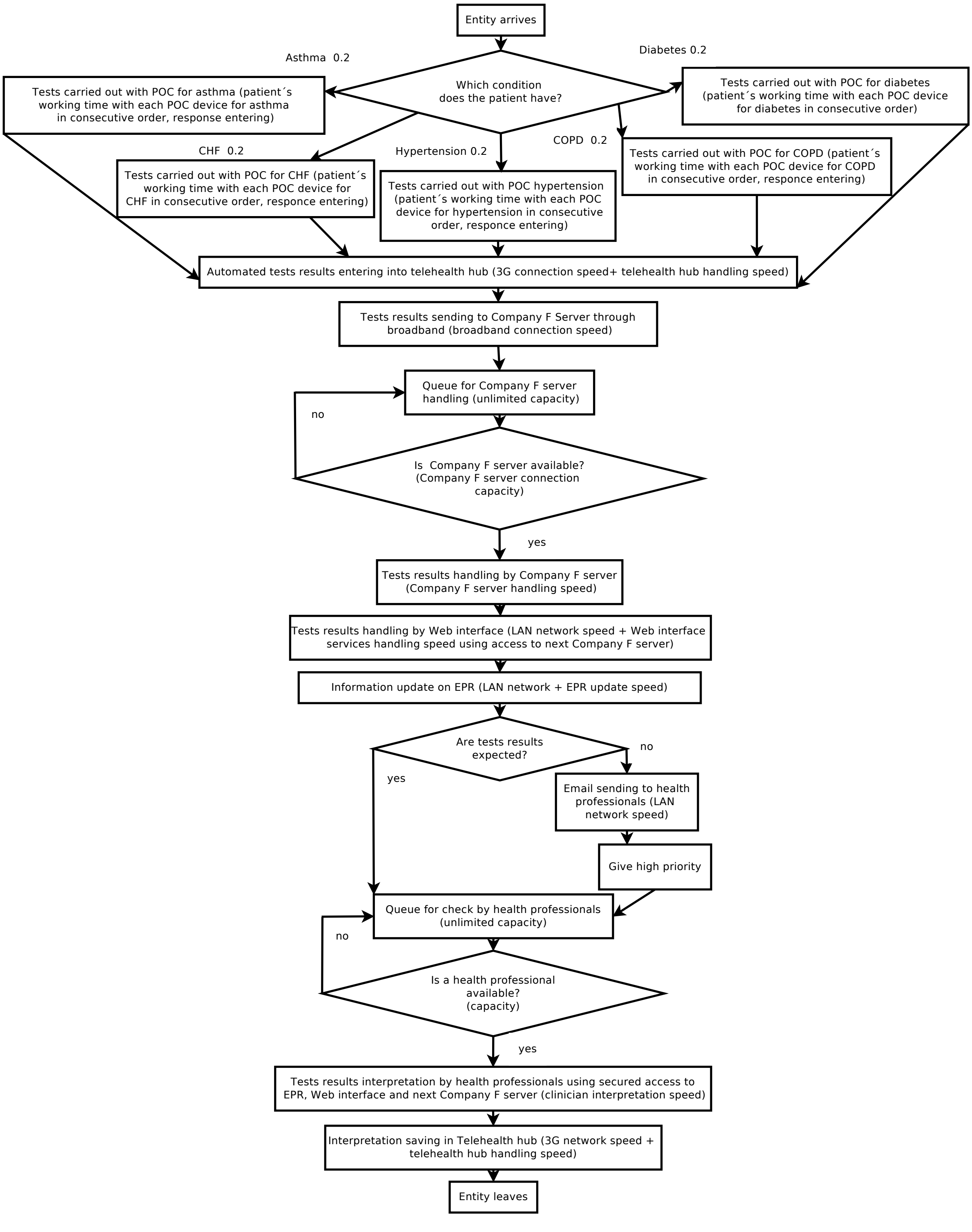


Figure 4.24: Final version of conceptual model for the Offering F

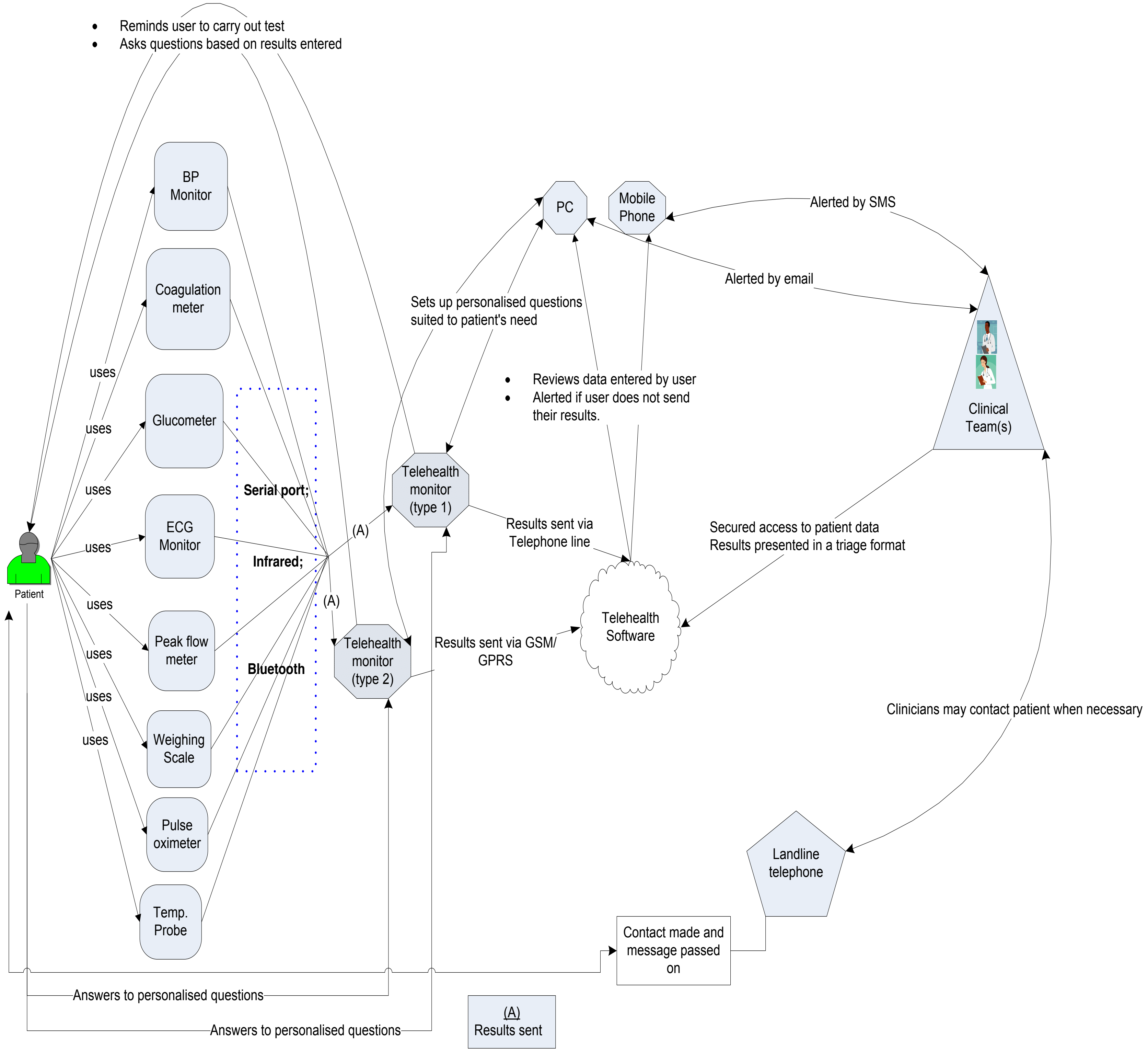
LAN network connects all these elements.

For the next activity relevant assumptions are A.1.11, A.1.13, A.1.14, A.1.15, A.1.10. The alerts are Short Messaging Service (SMS), e-mail or practice management system messages, but, according to the diagram, only the PC receives alerts. Thus only e-mail communication was left as the most common and logical for PC usage. Therefore, this activity is the same as in Offering A and is converted the same as in the Offering A.

The Offering F's tests results interpretation by the health professionals proceeds similarly as in the Offering A. The same assumptions are used: A.1.17 and A.1.12, and the tests results interpretation by the health professionals has been converted as in the Offering A.

The final activity of the Offering F is the tests results interpretation saved into a Telehealth hub. For this purpose, 3G network is used to send the interpretation, and the speed of the final activity depends on 3G network connection speed and a Telehealth hub saving speed. The A.1.10, A.1.22 were used.

The final DES conceptual model for Offering F is Figure 4.24.



Courtesy of Adeogun et al. (2011)

Figure 4.25: Data Flow Diagram for the Offering G

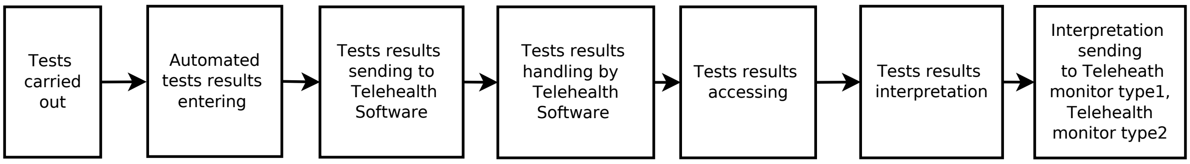


Figure 4.26: Process flow diagram for the Offering G

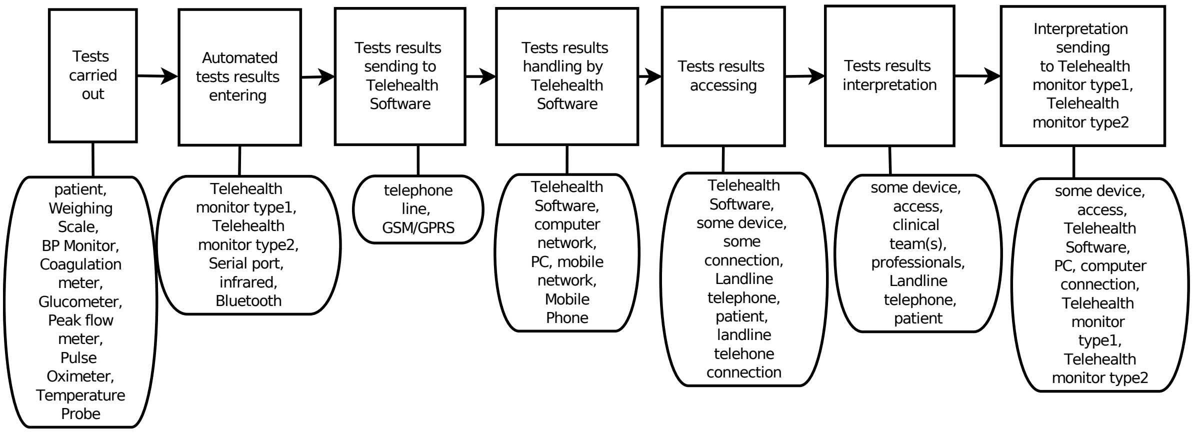


Figure 4.27: Process flow diagram with resources for the Offering G

4.2.7 Offering G

As with all previous offerings, the conceptual model building or design starts with the basic activities definition. Using the Data Flow Diagram for the Offering G Figure 4.25, publication Adeogun et al. (2011), and assumptions A.1.22, A.1.1, the Process flow diagram for the Offering G was created as Figure 4.26

Next step is similar to the previous offerings, but no assumption is used. The Process flow diagram with resources for the Offering G is Figure 4.27.

The tests carrying out activity has added in case, when the patient did not send any result. As patients use the telehealth system in their locations, this is not an emergency system and the probability of tests results not sending is small – 2%. In the test, the activity is similar to the other Offerings for monitoring several conditions with the responding entering and is similarly converted. Assumptions A.1.18, A.1.19 and A.1.3 are used.

The automated tests results entering activity is also very similar to the Offering B. The activity was converted using the same principles and assumptions:A.1.4, A.1.9, A.1.20 and A.1.7 were used.

The different types of the telehealth monitors use different connections to transfer the tests results to the telehealth software. The case reminds the Offering A, and the Offering A is used as a pattern of this activity conversion.

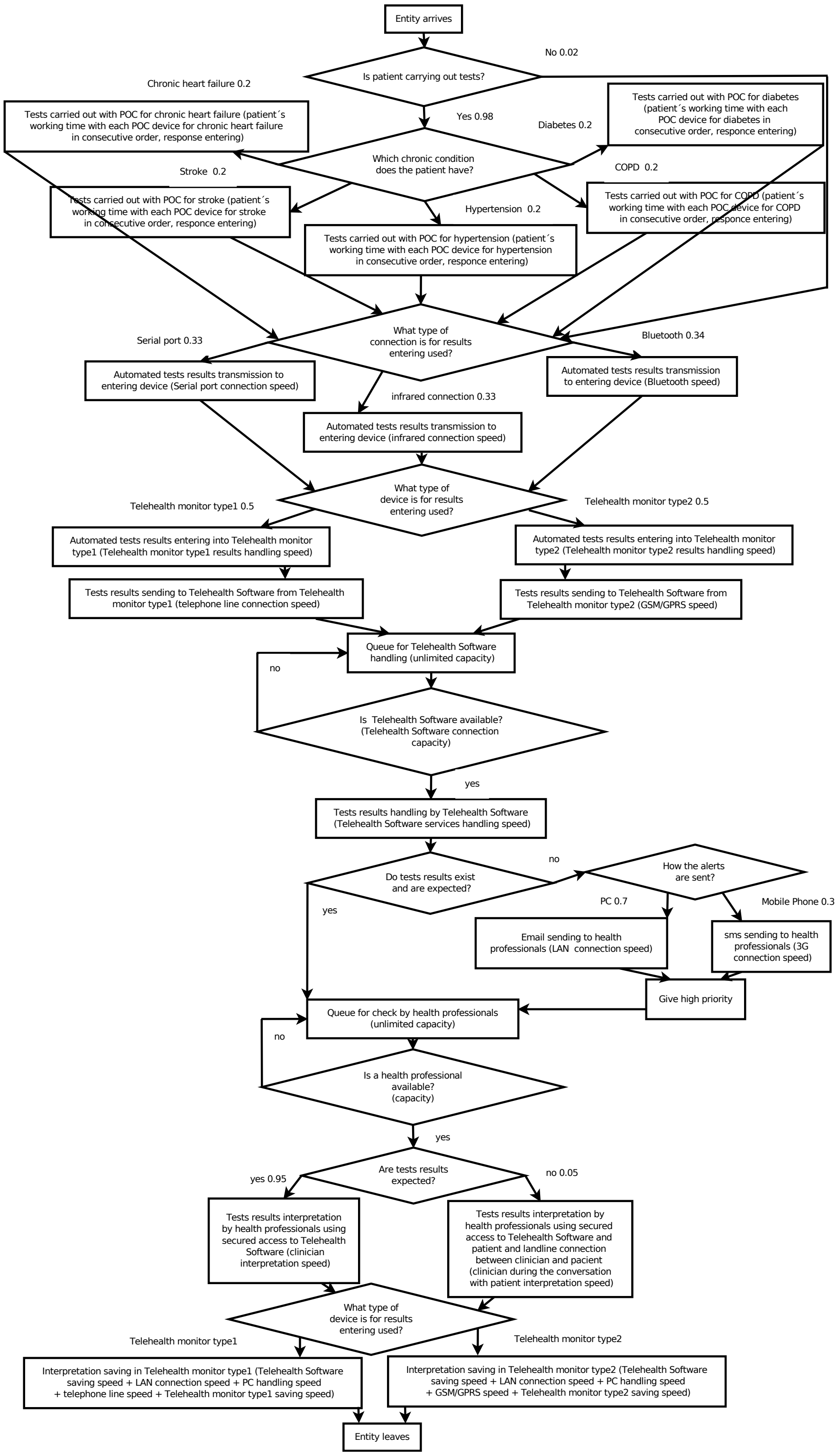


Figure 4.28: Final version of conceptual model for the Offering G

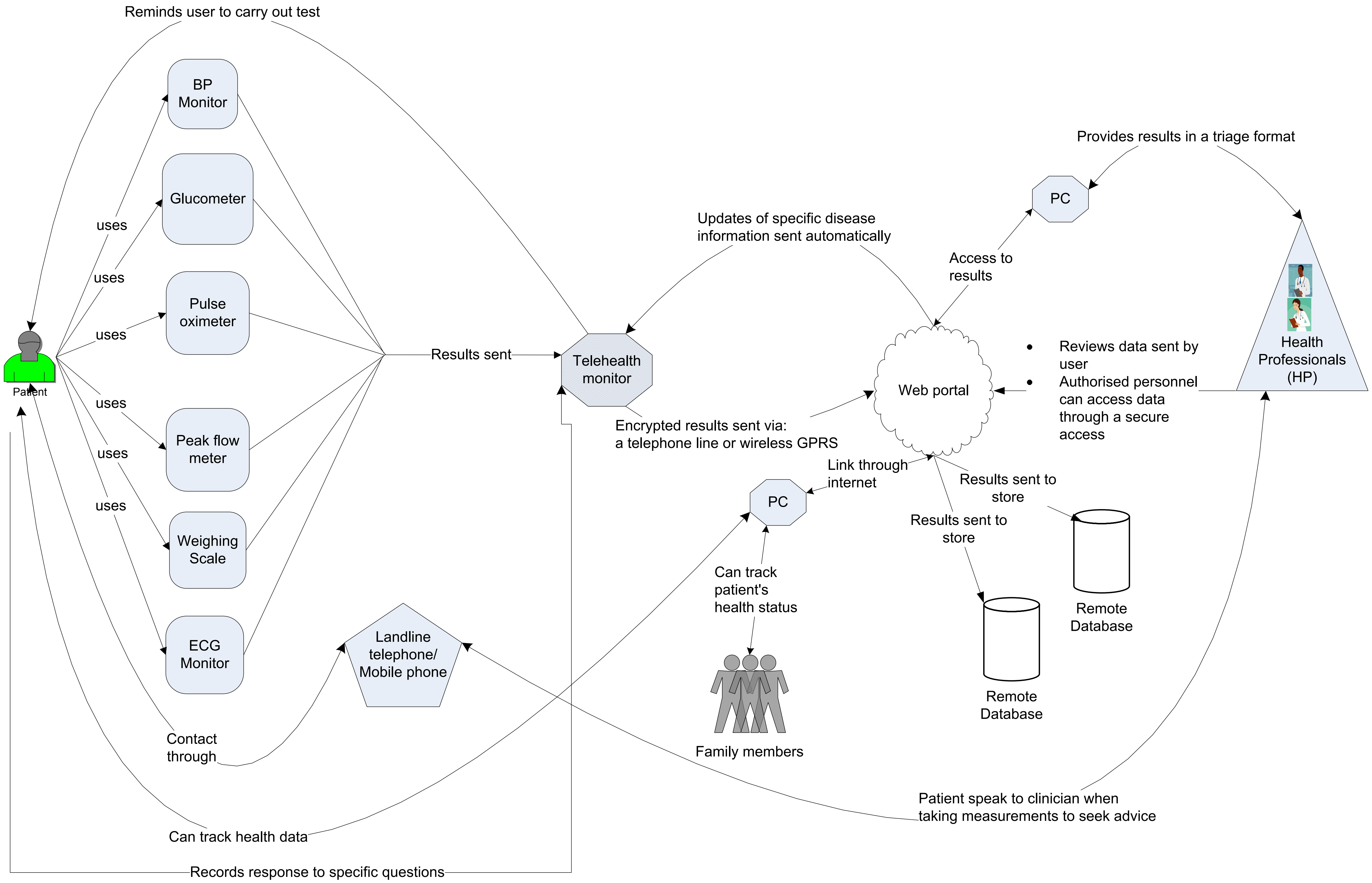
The tests results handling by the telehealth software activity also is similar to the Offering E and the same principles are used to convert this activity. The difference is that the telehealth software does not have an access to a server. The relevant assumptions for this activity are A.1.11, A.1.13, A.1.14, A.1.15, and A.1.8, A.1.10.

The next activity is excluded using assumption A.1.12.

The health professionals can contact a patient when necessary. The assumption is that this case has unexpected results. This activity is very similar to the Offering A. The difference is that if tests results are unexpected, the health professional interpret the results after speaking with the patient. As the patients are in their locations, then the relevant assumptions are A.1.17 and A.1.12. Thus, the tests results interpretation activity is converted similarly to the Offering A.

The tests results interpretation could be available to the patients only on one of the telehealth monitors. The telehealth monitor's usage depends on what type of the telehealth monitor was used for tests results entering. In addition, according to the telehealth monitor type, a certain type of connection for tests results saving is used. Therefore, the interpretation sending is divided and converted into the two elements: interpretation sending to telehealth monitor type1 and telehealth monitor type2. The speed of each element is calculated similarly to the Offering E, using each corresponding elements devices and connections. The A.1.10 was used.

The final DES conceptual model for the Offering G is Figure 4.28.



Courtesy of Adeogun et al. (2011)

Figure 4.29: Data Flow Diagram for the Offering H

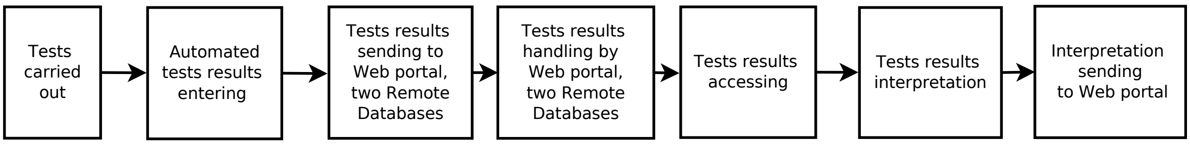


Figure 4.30: Process flow diagram for the Offering H

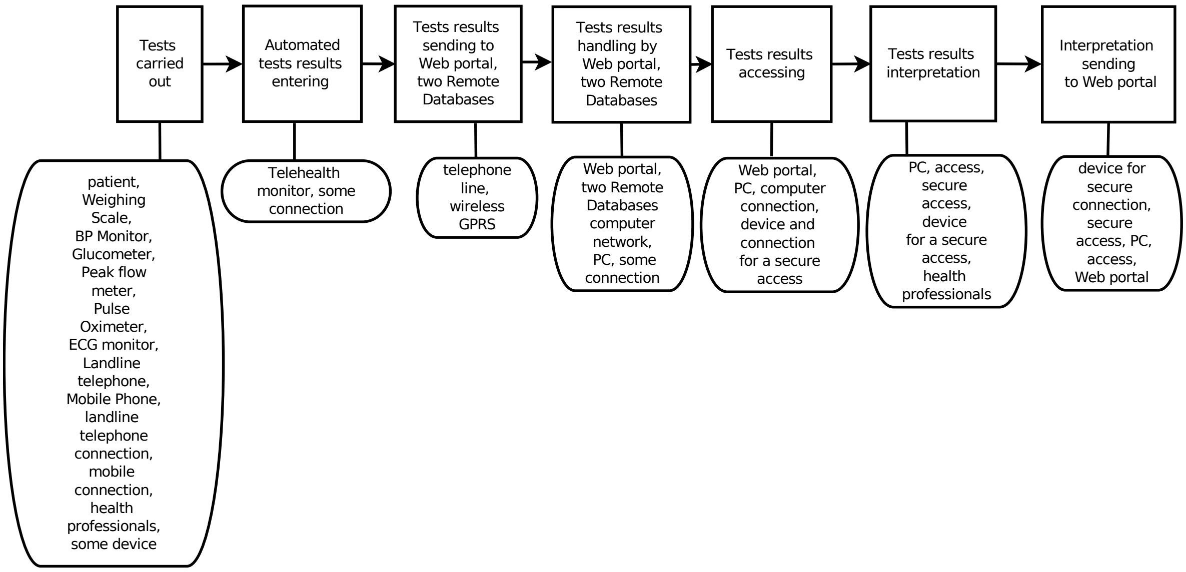


Figure 4.31: Process flow diagram with resources for the Offering H

4.2.8 Offering H

The conceptual model building or design starts as with the previous offerings with the basic activities definition. From the Data Flow Diagram for the Offering H Figure 4.29, and publication Adeogun et al. (2011) using assumptions A.1.22, A.1.1, the Process flow diagram for the Offering H was created Figure 4.30.

After adding the resources and actors, and assumption A.1.2 usage, the Process flow diagram with resources for the Offering H Figure 4.31 was constructed.

The tests carrying out activity proceeds in two ways: patient carries out tests without help or using a health professional's help. As the telehealth system was used to allow a patient to use the POC devices in their locations, it was assumed that patients are trained to work with POC devices. The health professional's help is needed rarely in 10% of the cases. The health professionals in the Offering H help the patients to carry out tests and interpret tests results. The health professionals give consultations to patients via a telephone. The calls need to have a high priority. The same principles as well as in the previous Offerings for several chronic conditions monitoring are used to convert each of the two cases of the tests carrying activities. Assumptions A.1.18, A.1.19 and A.1.3 are used.

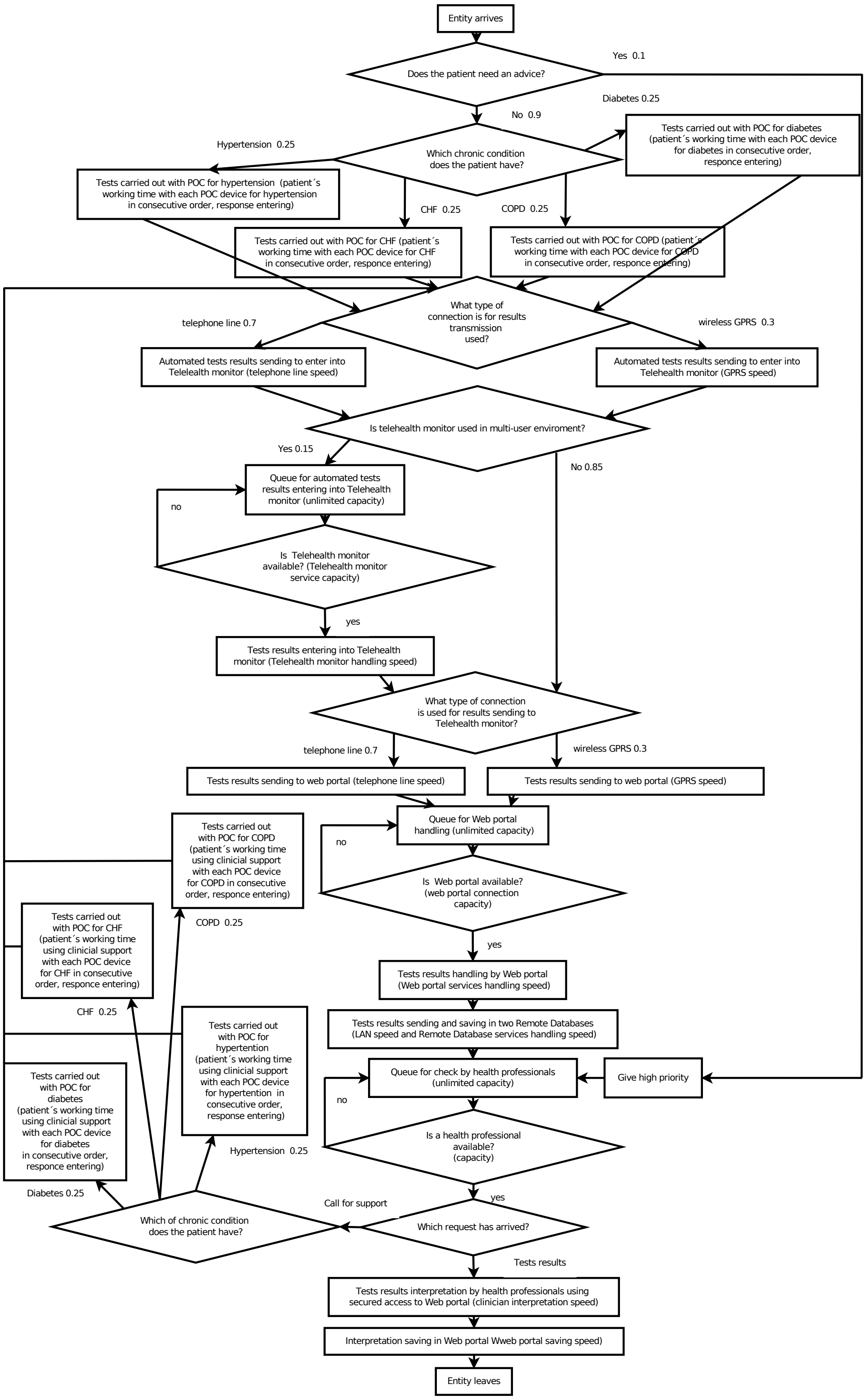


Figure 4.32: Final version of conceptual model for the Offering H

The tests results are sent to the entering device via two types of connections: a telephone line and the GPRS. The GPRS is used when a telephone line is not available, therefore the probability distributed between them is of 0.7 for the telephone line, and 0.3 for GPRS. The telehealth monitor can be used as a multi–user device. The probability of usage of the telehealth monitor as the multi–user device is 0.15. The automated tests results entering activity was converted similarly to the Offering E. The relevant assumption is A.1.4.

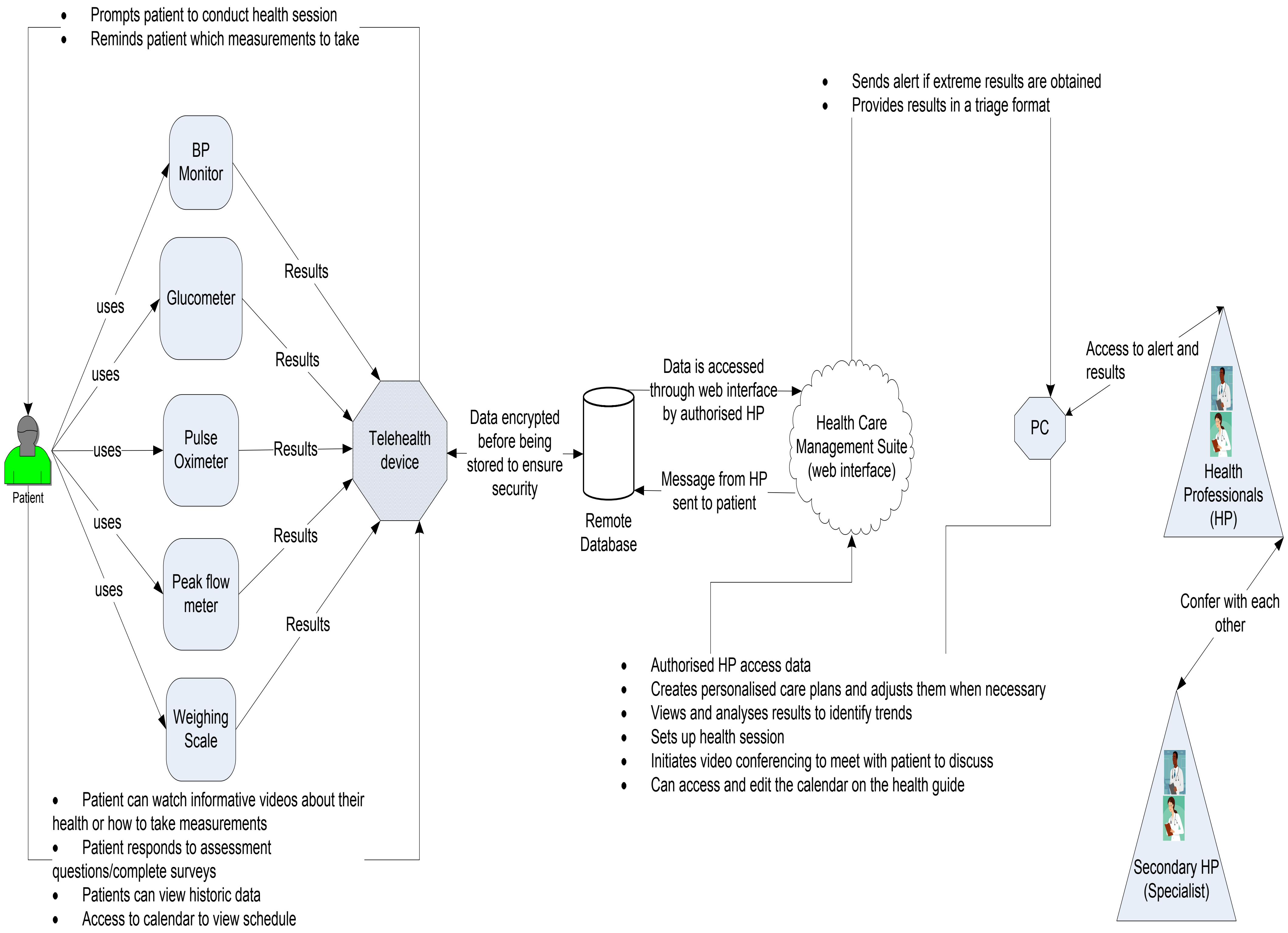
The next activity is the tests results transferring to a Web portal. The tests results are transferred via the two connections: a telephone line or the GPRS. This part of the activity is converted similarly to the Offering E. The principle of assumption A.1.20 is relevant for this activity.

The Web portal is the first common resource in the system. The Web portal sends tests results to the two remote databases. The remote databases handle the tests results in parallel; therefore, it is worthwhile to consider only one remote database. Thus, this activity is converted similarly to Offering F. The A.1.10 assumption is useful for this activity.

The Offering H's tests results interpretation by the health professionals proceeds similarly as in the previous offerings, but alerts are not sent and a high priority is given only to the patients' telephone calls. The same assumptions are used: A.1.17 and A.1.12.

The final activity of the Offering H is the tests results interpretation saved into the Web portal. The interpretation saved into the Web portal is converted similarly to the Offering C. For this purpose, a Broadband connection is used to send the interpretation and the speed of the final activity depends on the Broadband connection speed, and the telehealth hub saving speed. The A.1.12 assumption was used.

The DES conceptual model for the Offering H is represented by Figure 4.32.



Courtesy of Adeogun et al. (2011)

Figure 4.33: Data Flow Diagram for the Offering I

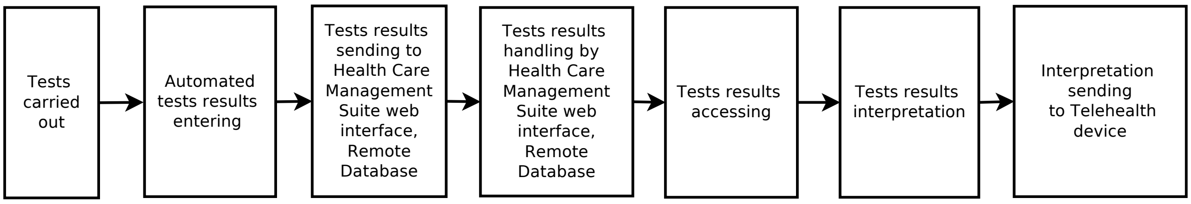


Figure 4.34: Process flow diagram for the Offering I

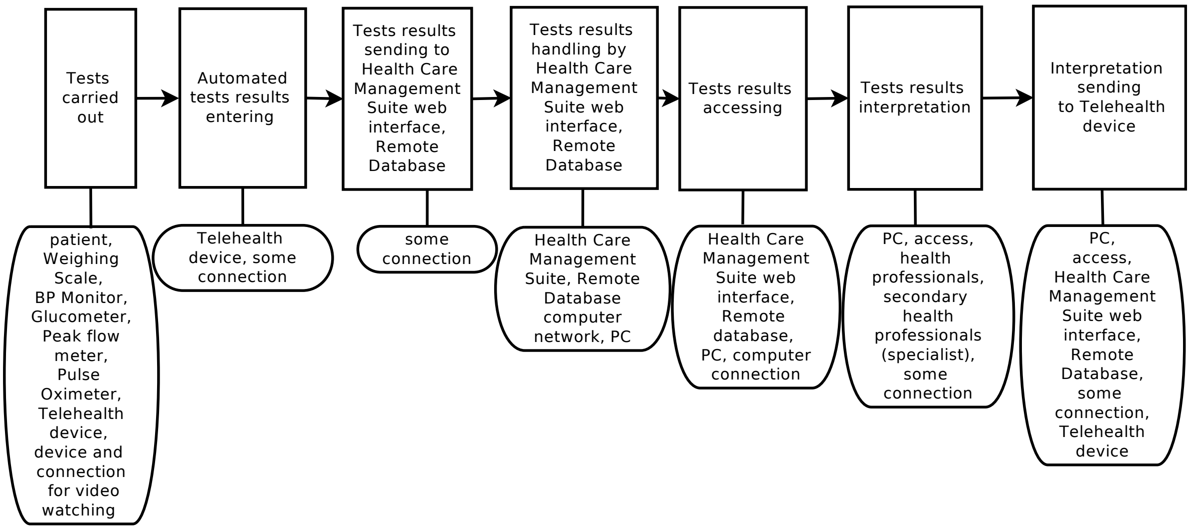


Figure 4.35: Process flow diagram with resources for the Offering I

4.2.9 Offering I

As with the previous offerings, the conceptual model design or the building procedure 3.1 starts with the basic entity processing activities definition. The available information is represented by Data Flow Diagram for the Offering I, Figure 4.33 and in publication Adeogun et al. (2011). Assumptions A.1.22, A.1.1 were used to create the Process flow diagram for the Offering I, Figure 4.34

The next step of the DES conceptual model design or building requires to add the resources and actors to each activity from Figure 4.34. Finally, the Process flow diagram with resources for the Offering I Figure 4.35 was constructed.

The tests carrying out activity is similar to the Offering F, and it is converted similarly, considering a difference in the diseases, the POC device and the added videos. Assumptions A.1.18, A.1.19 and A.1.3 are used.

As the Offering F, the Offering I used only one entering device, therefore, this activity can also be converted similarly to the Offering F. A telehealth device on its functionality and technical characteristics are very similar to the telehealth monitor and the similar data was used.

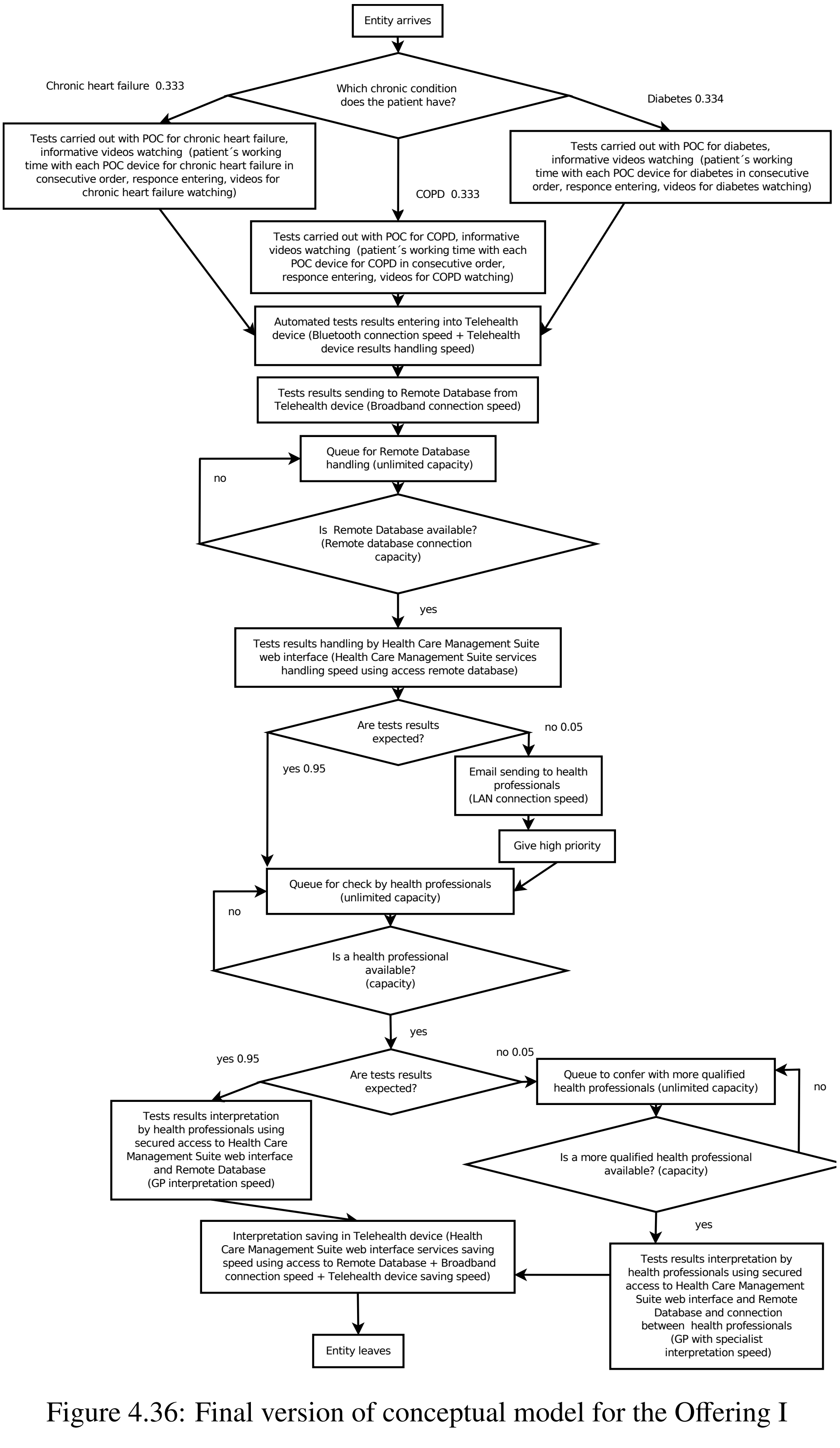


Figure 4.36: Final version of conceptual model for the Offering I

It was assumed that Bluetooth connection is used to transfer tests results from the POC device to a telehealth device. Assumptions A.1.9 and A.1.4 are relevant for this activity.

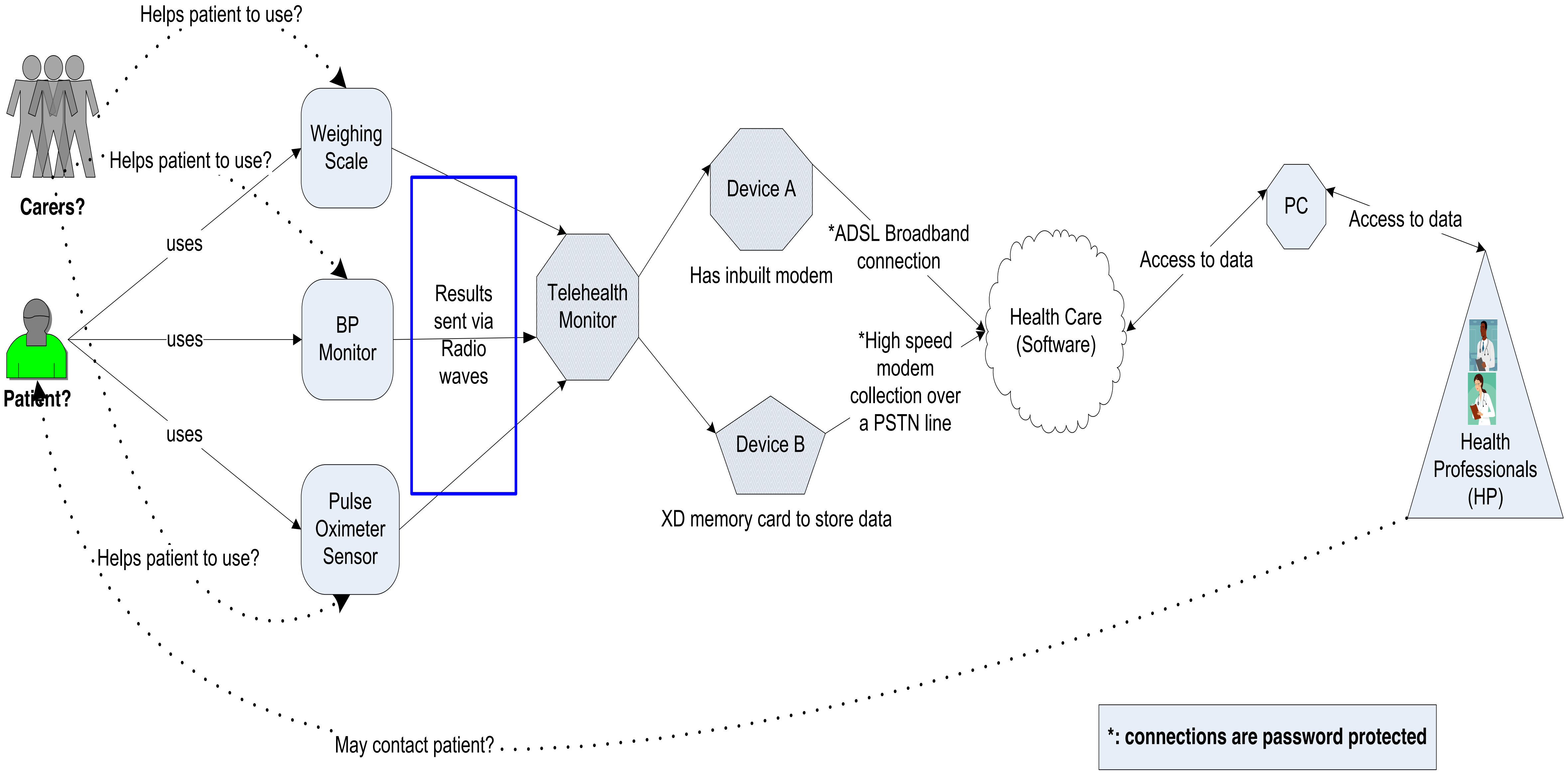
The next activity transfers the tests results from the entering device to a remote database. This activity was converted similarly to the Offering F, but only one type of connection was used. The Broadband connection was chosen as connection between the telehealth device and Heath Care Management Suite Web interface.

The remote database is accessible through the Web interface, this principle is similar to the Offering E, and the tests results handling by the Heath Care Management Suite Web interface is converted similarly. Only a PC is used to view alerts in the Offering I. Alerts sending is similar to the Offering F and is converted similarly. The assumptions A.1.11, A.1.13, A.1.10, A.1.14, and A.1.15 are used.

As the Offering E and the Offering I involve two types of the health professionals – GPs (primary) and specialists (secondary) Adeogun et al. (2011). That is why the same conversion principles can be used for Offering E. The assumptions A.1.21, A.1.17 and A.1.12 are also relevant for this activity.

The final activity is the tests results interpretation saving in the telehealth device. This activity conversion for the Offering E can also be used as a pattern for the Offering I considering corresponding device and connections. The assumptions A.1.22, A.1.12, need to be used for the final activity.

The result of the conceptual model design or building procedure 3.1 for the Offering I is Figure 4.36.



Courtesy of Adeogun et al. (2011)

Figure 4.37: Data Flow Diagram for the Offering J

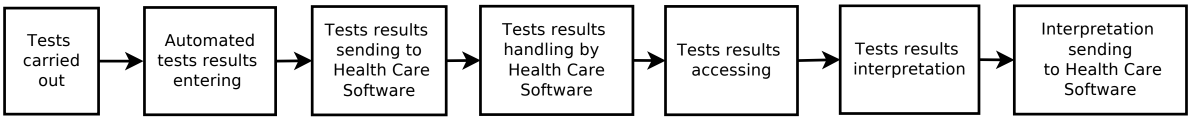


Figure 4.38: Process flow diagram for the Offering J

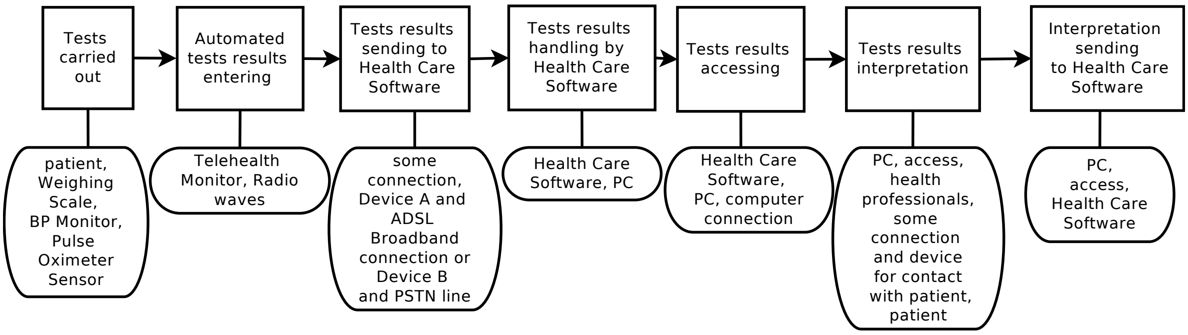


Figure 4.39: Process flow diagram with resources for the Offering J

4.2.10 Offering J

The conceptual model design or the building procedure 3.1 starts with the basic activities definition. Using the Data Flow Diagram for the Offering J Figure 4.37, publication Adeogun et al. (2011) and the assumptions A.1.22, A.1.1 were created the Process flow diagram for the Offering J Figure 4.38

The next step of the DES conceptual model design or building is also similar as the on previous offerings. The role of the carers is defined more clearly in the Offering J, than in the other, offerings but it is also too vague to define their influence in the system and the assumption A.1.2 is used. The Process flow diagram with resources for the Offering J is Figure 4.39.

The Data Flow Diagram for the Offering J Figure 4.37 provides a data only about the used POC devices. Usually, a description of an Offering provides two pieces of information – a list of sicknesses given Offering is serving and a list of POC devices. In case of the Offering J, only a list of POC devices is available. Thus, conditions that are monitored by this telehealth system have to be decided upon. During the previous offerings, many conversion data was collected and it can be used to check the widespread conditions, and the POC devices for their monitoring. It was assumed that at least one POC device is enough to monitor the chronic condition. If Offering J deploys a POC device used for monitoring of a certain condition, than Offering J is considered to be providing services of monitoring of that condition. The assumptions A.1.18, A.1.19, and A.1.3 are used to convert this activity. Therefore, the two basic cases need to be converted similarly to the previous offerings for monitoring several conditions.

The automated rests results entering in the Offering J is similar to the Offering I: use only

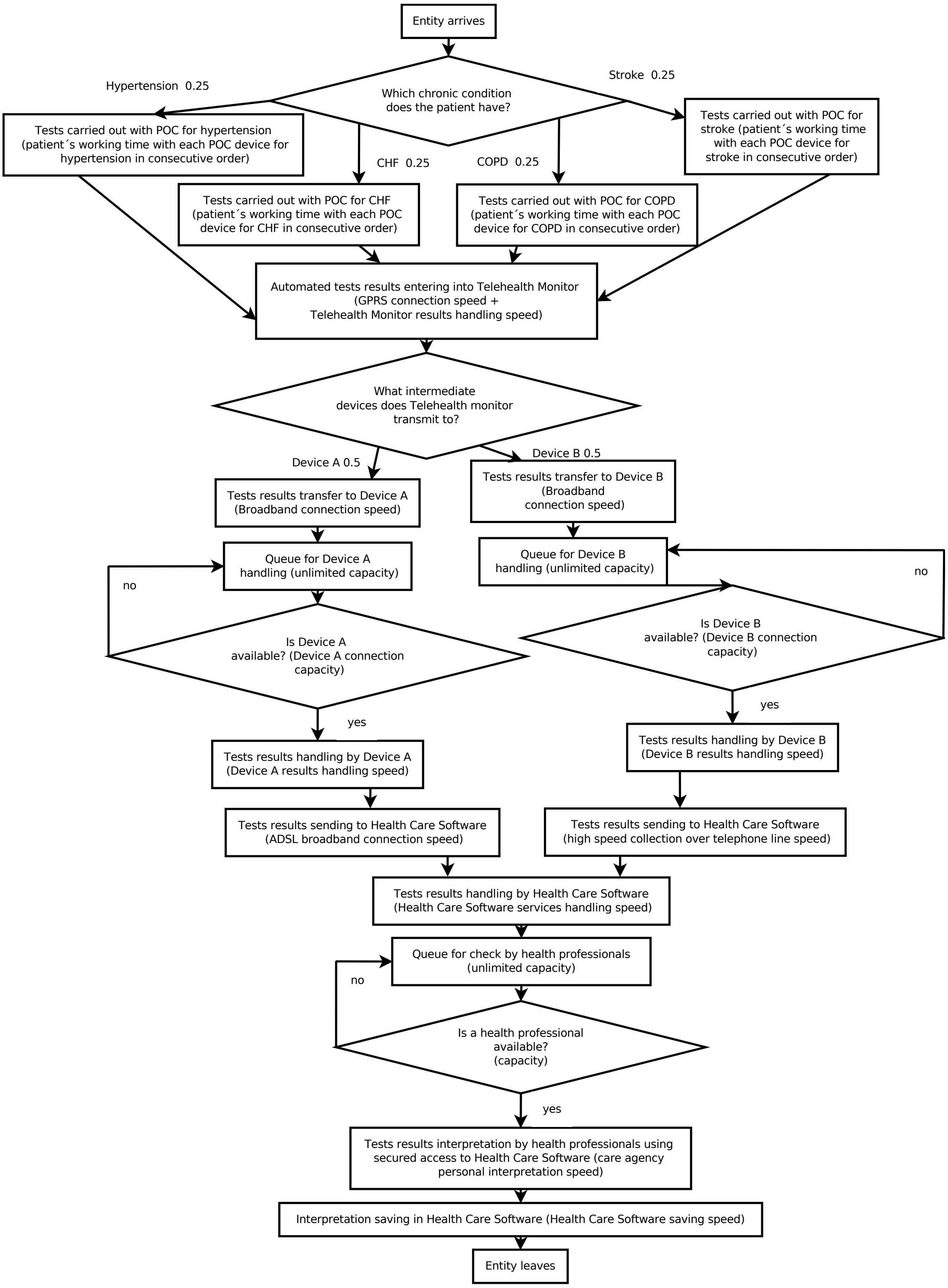


Figure 4.40: Final version of conceptual model for the Offering J

one entering device and results are sent via the radio waves. Therefore, this activity can also be converted similarly to the Offering I. The assumptions A.1.9, and A.1.4 are relevant for this activity.

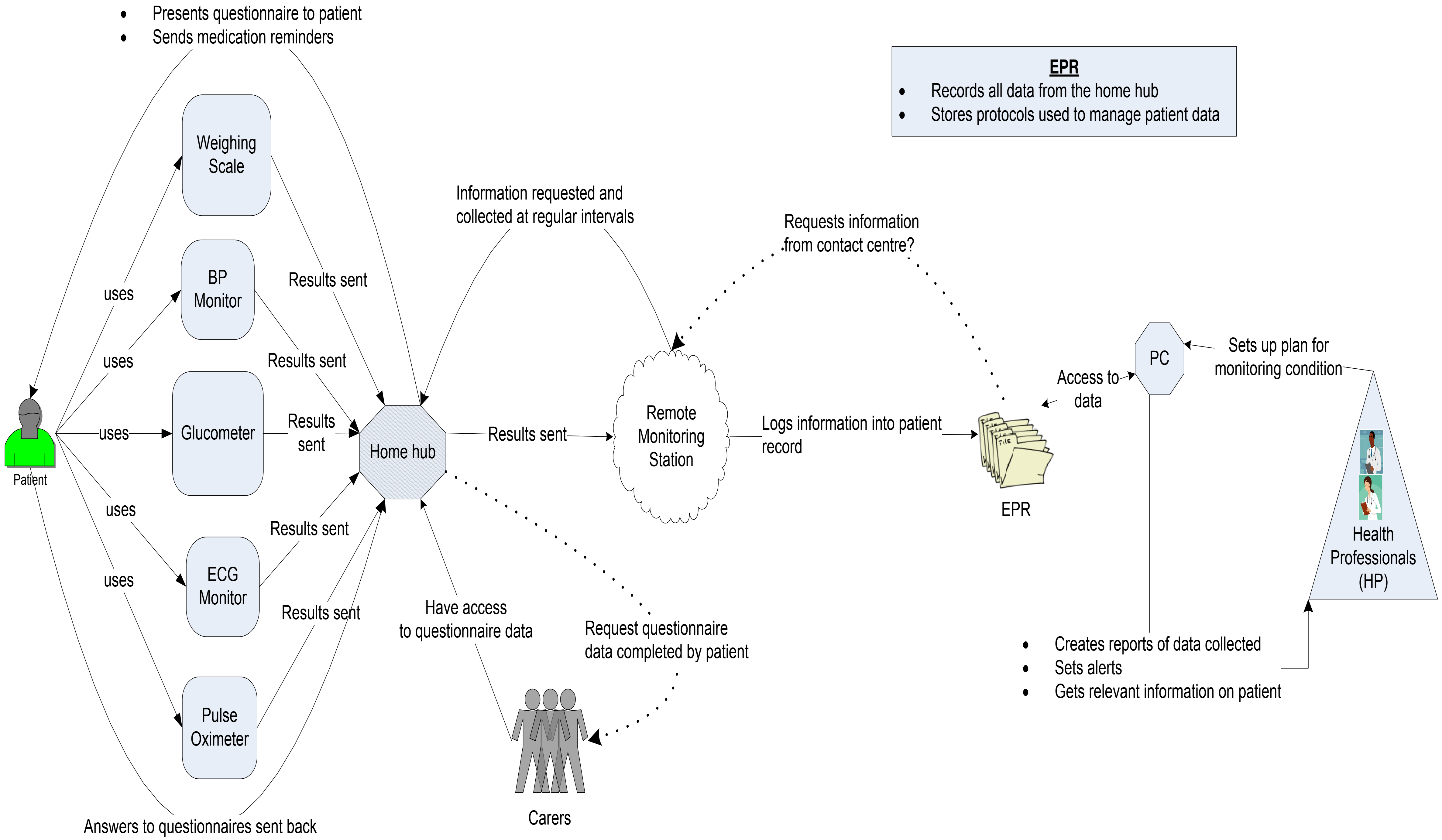
The first common devices on the entity path are Device A and Device B. As Device A and Device B stores data about the patients, most likely they are not located at the patients' home. Device A and Device B use a Broadband connection as the most popular connection. The assumptions A.1.20, A.1.9, and A.1.7 are used in this activity. This activity was converted similarly to the previous offerings activities with several devices for the same usage and the first common devices conversion.

After Device A or Device B, the entity or the tests results reach the health care (software). Tests rests results are transferred from Device A or Device B through a Broadband and Public Switched Telephone Network (PSTN) line respectively. The PSTN line was chosen as the most widespread. This is the second common resource on entity's path. As health care software receives tests results from the several devices, the queue can form and it has to be included. This activity is converted similarly to the Offering F, EPR updating activity as the most similar to health care software. Alerts are not sent in the Offering J and the Offering C and are converted similarly.

The Offering J contains one type of the health professionals, similarly to the Offering F, but in the Offering J, the health professionals access only the health care software and the tests results interpretation is converted similarly. The assumptions A.1.17, and A.1.12 also need to be used for this activity.

The last activity is the tests results interpretation saving in a place where it is available for the patients. The Data Flow Diagram for the Offering J Figure 4.37 and Adeogun et al. (2011) do not contain a data on how the patients receive their results interpretation. Only this phrase: "May contact patient?" on the dashed line from Health Professionals to Patients remotely looks like the useful information. However, how and how often do the health professionals contact patients, what devices to use and how this connection password is protected, are unknown. Therefore, this is excluded from the model. Nevertheless, the last device, which can store tests results interpretation, is health care software. Thus, the last activity is the interpretation saving in health care software. This activity conversion for the Offering I is used as a pattern for the Offering J considering corresponding device and connections. The assumptions A.1.22, and A.1.12 are relevant for the last activity.

The Final version of conceptual model for the Offering J is Figure 4.40.



Courtesy of Adeogun et al. (2011)

Figure 4.41: Data Flow Diagram for the Offering K

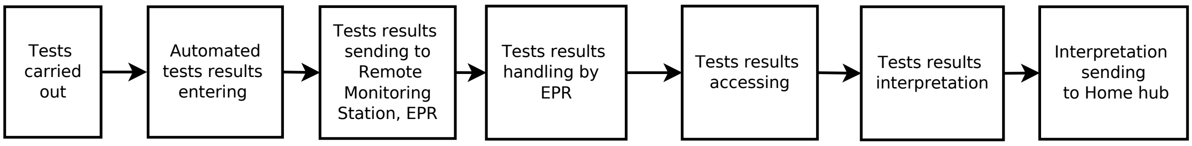


Figure 4.42: Process flow diagram for the Offering K

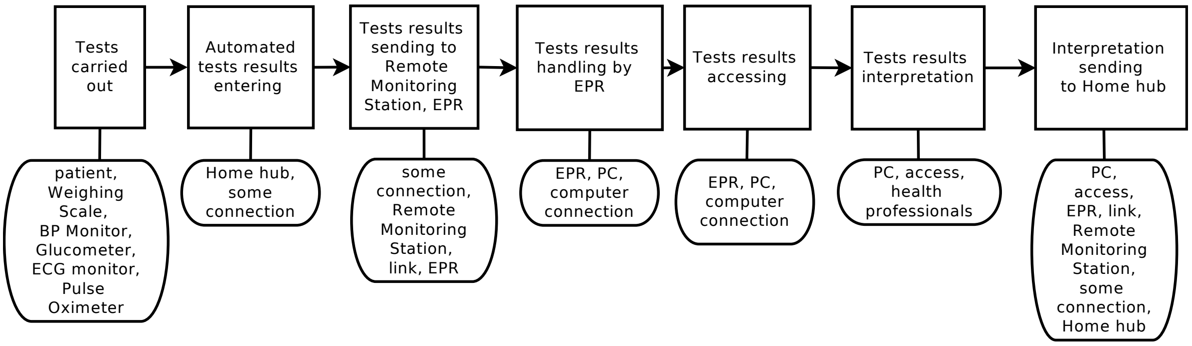


Figure 4.43: Process flow diagram with resources for the Offering K

4.2.11 Offering K

The conceptual model design or building procedure 3.1 requires to start with the basic entity processing activities definition. The available information is represented by the Data Flow Diagram for the Offering K, Figure 4.41, and in publication Adeogun et al. (2011). The assumptions A.1.22, A.1.1 are relevant to get the Process flow diagram for the Offering K, Figure 4.42

For the next step resources and actors need to be added to each activity from Figure 4.42. The assumption A.1.2 is relevant for this step. The Process flow diagram with resources for the Offering K is the Figure 4.43.

The tests carrying out activity is similar to the Offering J, and is converted similarly using the same principles. However, the Offering K patients do not need the consultation during the tests carrying out activity. The assumptions A.1.18, A.1.19 and A.1.3 are used.

The Offering J and the Offering K use only one entering device. Therefore, this activity is also converted similarly to the Offering J. The assumptions A.1.9, A.1.10, and A.1.4 need to be used.

The next activity is tests results transferring from telehealth hub to remote monitoring station. In addition, the Offering E uses the telehealth hub as the entering device. This activity was converted similarly to the Offering E, considering that one type entering device is used. The assumption A.1.10 has to be used.

The remote monitoring station receives the entities or tests results from all the patients,

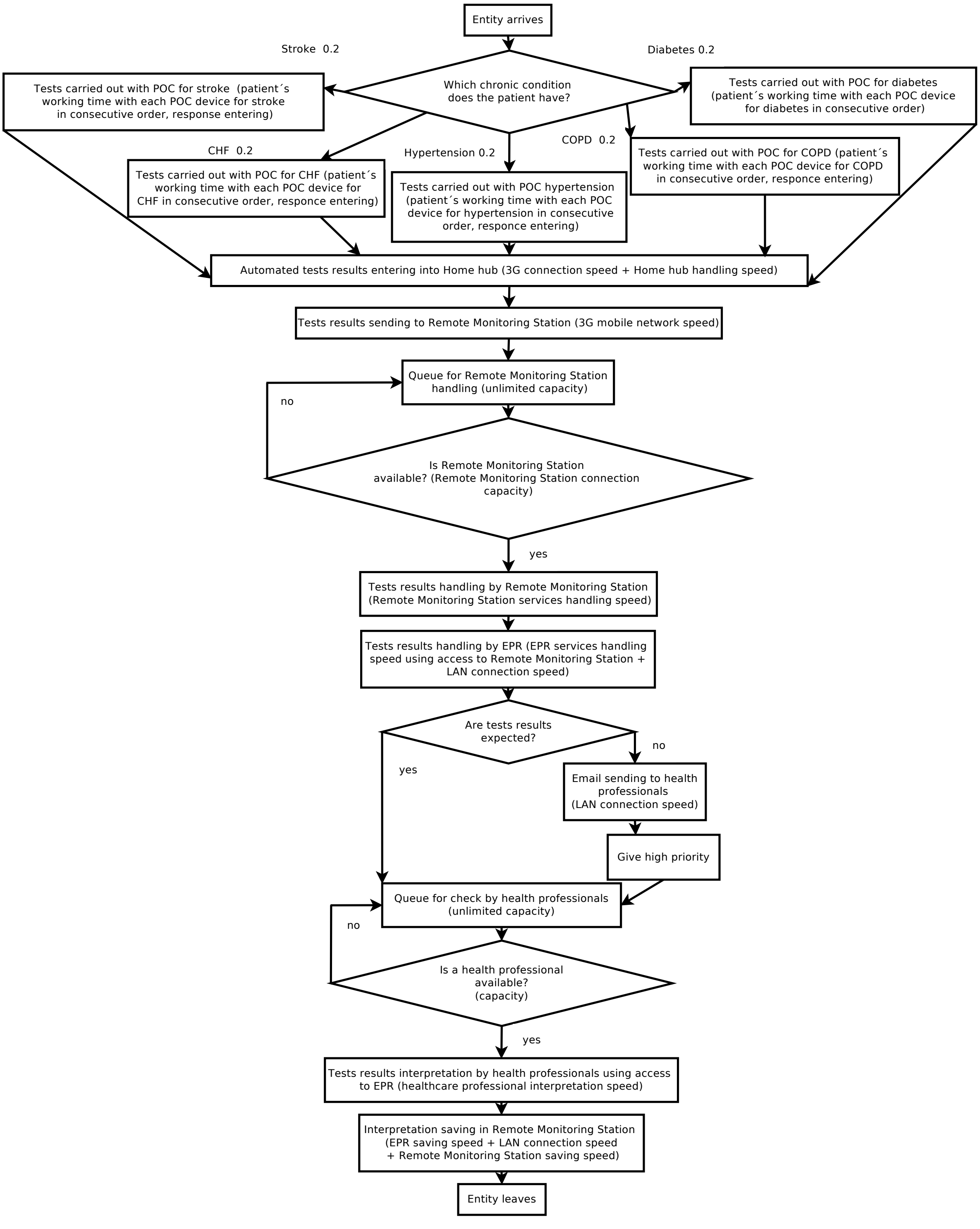


Figure 4.44: Final version of conceptual model for the Offering K

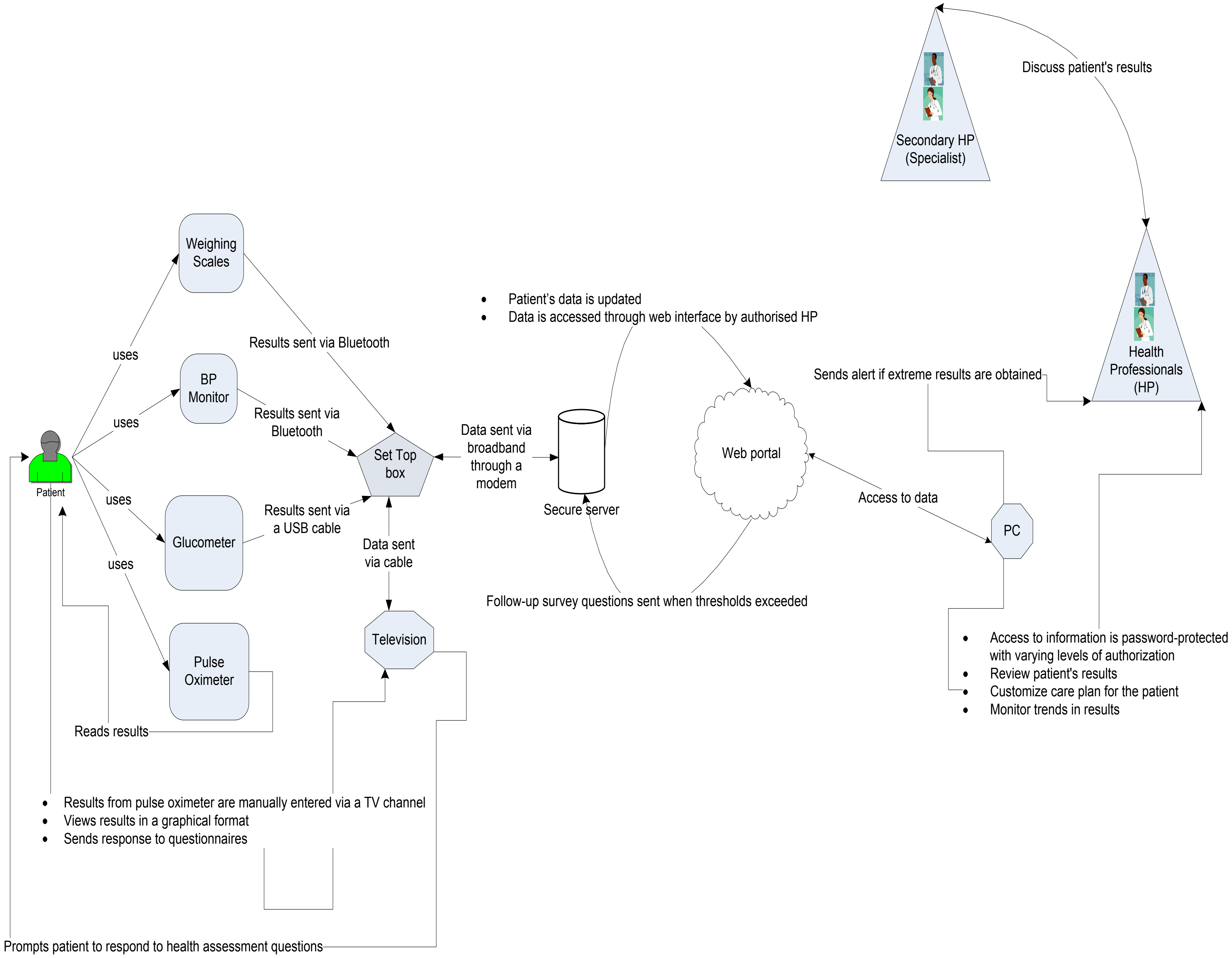
therefore, they are converted similarly to all offerings' handling by the first common resources activity.

After the remote monitoring station tests results are handled by EPR, this activity in the Offering K is similar to the same activity in the Offering B. The Offering B conversion is used as a pattern for the Offering K. But alerts are sent only to a PC. The assumptions A.1.11, A.1.13, A.1.10, A.1.14 and A.1.15 are used.

The tests results interpretation by the health professionals activity is similar to the Offering J and is converted similarly to the Offering J. The assumptions A.1.17, and A.1.12 are useful for this activity.

The last activity requires making the tests results interpretation available to the patient by saving in the remote monitoring station. This activity is similar to all the previous offerings and will be converted similarly considering corresponding device and connections. The assumptions A.1.22, A.1.10 and A.1.12 are used for the final activity.

The DES Final version of conceptual model for the Offering K is Figure 4.44.



Courtesy of Adeogun et al. (2011)

Figure 4.45: Data Flow Diagram for the Offering L

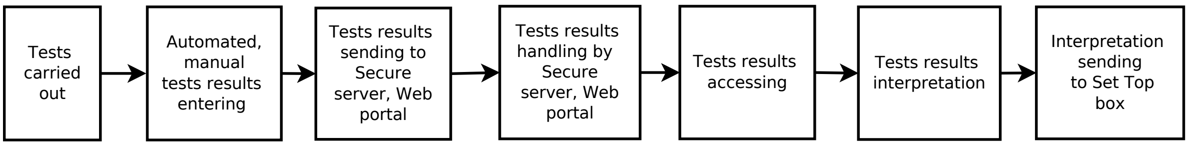


Figure 4.46: Process flow diagram for the Offering L

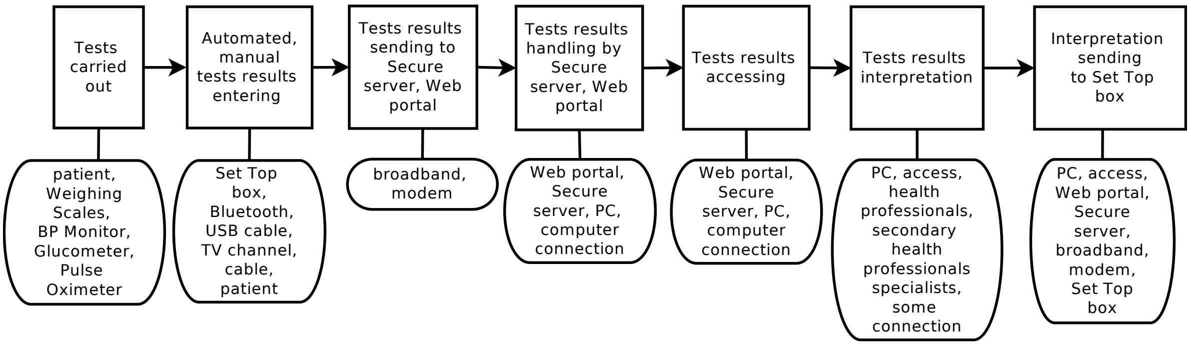


Figure 4.47: Process flow diagram with resources for the Offering L

4.2.12 Offering L

The conceptual model design procedure 3.1 should be started with the basic entity or tests results processing activities definition. Using the Data Flow Diagram for the Offering L, Figure 4.45, publication Adeogun et al. (2011) and the assumptions A.1.22, A.1.1 the Process flow diagram for the Offering L was created and presented by the Figure 4.46

The next step of the DES conceptual model design or building requires to add resources and actors to each activity from the Figure 4.46. For every elements of the Figure 4.45 need to have a corresponding activity. The result of this step is the Process flow diagram with resources for the Offering L, Figure 4.47.

The Offering L was provides services for monitoring of a several. Many previous offerings also monitored several conditions and this experience is used to convert this activity. The assumptions A.1.18, A.1.19, and A.1.3 also are used.

As different POC devicess use different connections to send the results to the entering device, even more, response and results from a pulse oximeter are manually entered via a TV channel and sent to the entering device via cable. This activity can be converted similarly to the Offering B, where the same principle was used for entering devices. The relevant assumptions here are A.1.4, A.1.9, and A.1.20. The Offering L use only one type of entering devices, thus, only a set top box handling speed has to be added to complete this activity conversion. The set top box is in fact, a TV set and the assumption is, its speed is similar to PC. The channel cable speed is the similar to the Broadband.

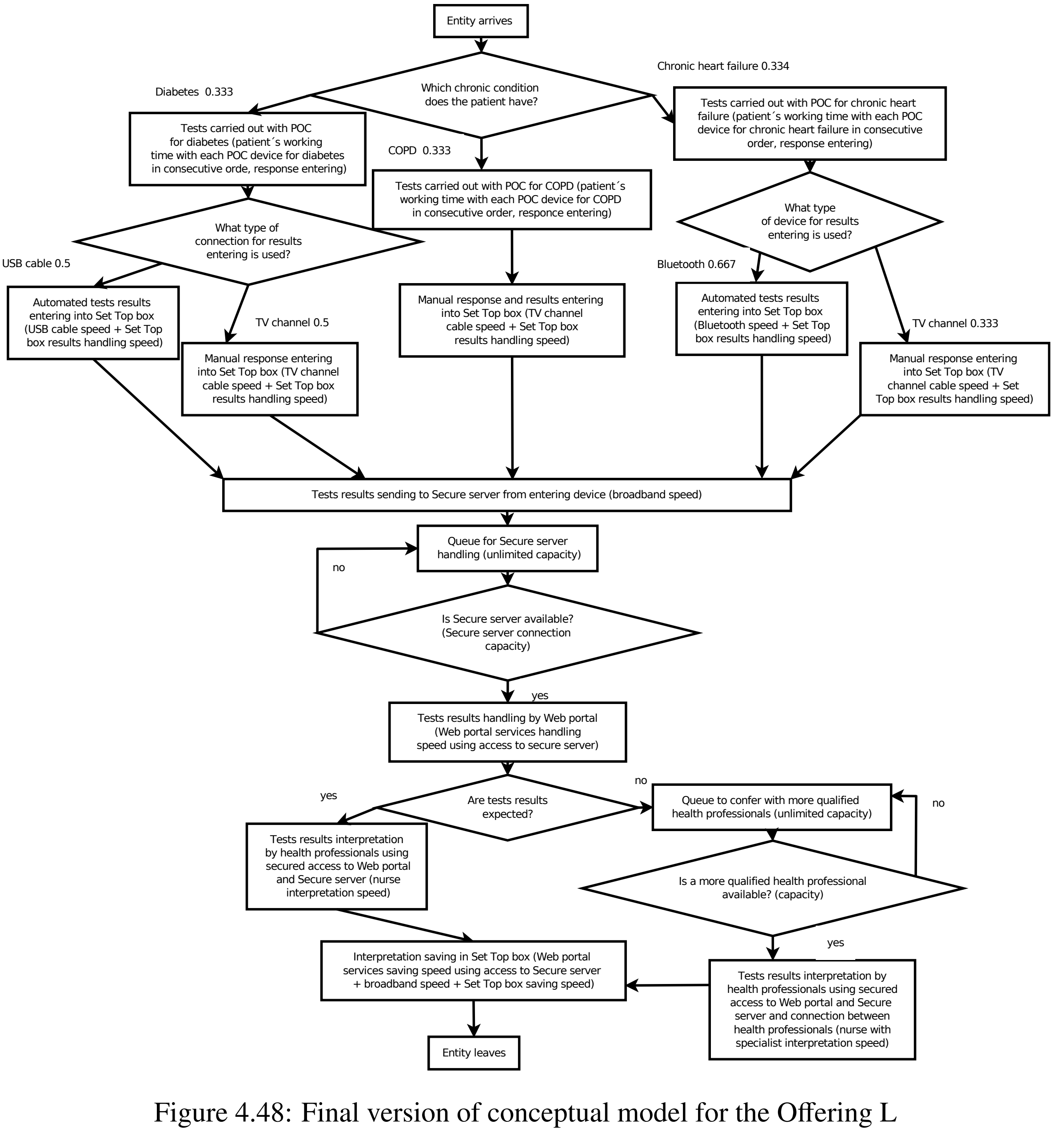


Figure 4.48: Final version of conceptual model for the Offering L

The tests results are transferred using one type of connection. This activity is similar to the Offering L and is converted similarly. In addition, the alert sending is converted similarly to Offering I. The assumptions A.1.11, A.1.13, A.1.14, A.1.15 and A.1.8 were used.

The entity or tests results interpretation is performed by the two types of health professionals; Nurses (primary) and specialists (secondary) Adeogun et al. (2011). Thus, the principles used in the Offering I principles are also applicable for the Offering L. The assumptions A.1.21, and A.1.12 are relevant for this activity.

The last activity of the entity or tests results processing in the Offering L is the interpretation saving in Set Top box. The conversion of this activity is carried out as in the previous offerings considering corresponding entity path to the Set Top box. The assumptions A.1.22 and A.1.12 need to be used for this activity.

The final DES conceptual model for the Offering L is represented by the Figure 4.48.

4.3 Outputs of the DES models

It was defined in section 3.3, a maximum and an average entity time (measured in minutes) in a system had been collected for all the modelled telehealth systems. Results are provided in Table 4.1 for the review.

It is clear from the Table 4.1, the raw simulation results are not normalised. For example, the average and maximum time in the system values for the Offering D, are in line with the appropriate values for the other systems. But it is evident that this is not right. For example, the Offering D has saturation density of 0.7 msg/min, while the saturation density for most (all but not the Offering H) of the other systems is in 2 msg/min to 3 msg/min.

Thus, it is evident that time in the system should be normalised. In this thesis, the simplest way of maximum/average time normalisation is proposed – dividing an 'average time' number provided in Table 4.1 by incoming message density used for that particular experiment. The table with the new, normalised minimum and maximum time in a system can be found in the Table 4.2. Please note that given table (4.2) also features the 'cost of single message' metrics, that was calculated according to the algorithm described in sub–section 3.3.5. Please refer to the Equation 3.1 for the actual formulae used.

Table 4.1: Simulation results (Time measured in minutes. Saturation density is the number of messages per minute)

		100% saturation		80% saturation		50% saturation	
Offering	Saturation density	Max	Avg	Max	Avg	Max	Avg
A	3.43	138.116	73.753	69.258	36.853	20.424	17.600
B	3.49	149.683	78.863	79.313	44.336	55.609	32.008
C	5.23	143.598	78.503	75.147	44.042	30.360	21.935
D	0.70	141.031	72.438	81.447	38.715	56.792	22.113
E	3.83	137.315	67.671	84.831	45.573	22.029	8.772
F	3.00	133.635	42.367	38.012	22.421	34.271	21.734
G	3.09	136.909	75.383	85.271	46.486	78.323	44.087
H	1.98	115.594	68.517	57.339	33.551	50.115	31.165
I	3.33	149.938	87.151	84.026	55.946	63.818	45.267
J	6.45	99.118	57.800	34.947	97.209	32.127	22.662
K	3.23	114.090	64.674	68.581	38.031	50.337	33.161
L	3.28	113.508	57.490	53.369	29.301	36.612	23.287

Table 4.2: Simulation results, normalised to capacity (Time measured in minutes. Saturation density is the number of messages per minute)

		100% saturation			80% saturation			50% saturation		
Offering	Saturation density	Max	Avg	Cost	Max	Avg	Cost	Max	Avg	Cost
A	3.43	40.267	21.502	3.650	25.240	13.430	4.560	11.909	10.262	7.300
B	3.49	42.889	22.597	3.580	28.407	15.880	4.490	31.868	18.343	7.180
C	5.23	27.457	15.010	2.650	17.961	10.526	3.310	11.610	8.388	5.290
D	0.70	201.477	103.485	29.340	145.455	69.141	36.680	162.278	63.186	58.690
E	3.83	35.853	17.669	3.900	27.686	14.874	4.880	11.503	4.581	7.810
F	3.00	44.545	14.122	4.170	15.838	9.342	5.220	22.847	14.489	8.350
G	3.09	44.307	24.396	4.050	34.495	18.805	5.070	50.695	28.535	8.110
H	1.98	58.381	34.605	6.330	36.199	21.181	7.910	50.621	31.480	12.650
I	3.33	45.026	26.171	4.490	31.541	21.001	5.610	38.329	27.188	8.980
J	6.45	15.367	8.961	0.870	6.773	18.839	1.080	9.962	7.027	1.730
K	3.23	35.322	20.023	3.880	26.541	14.718	4.850	31.169	20.533	7.750
L	3.28	34.606	17.527	4.560	20.339	11.166	5.700	22.324	14.199	9.120

Chapter 5

Discussion

5.1 Simulation Results Comparison

For this comparison, it was decided to use both, the normalised and non–normalised data to be able to evaluate the quality of the proposed normalisation procedure.

After carefully examining the graphical depiction of the normalised (Figure 5.1, Figure 5.2) and non–normalised (Figure 5.4, Figure 5.5) results, one can arrive at a conclusion that the overall system dynamics is close to what one could expect the given level of abstraction of the current work. Both maximum and average times in the system increase as systems' load approaches by 100% and decreases when the load reduces.

The most obvious outsider is, of course, the Offering D. It seems to have the highest processing cost constantly and more time in the system (both maximum and average). This can be attributed to the structure of the given Offering. In the Offering D, the telehealth system is implemented in the least automated way – all processing is done by the humans and virtually no automation of this process is present.

One notable exception of this behaviour seems to be the Offering J, as it has an unexpected increase in the non–normalised Average time in the system vs the saturation density (non–normalised) (Figure 5.4). However, at the same time, Offering J has not shown abnormal behaviour nor in the Maximum time in the system vs the saturation density (non–normalised) (Figure 5.5) nor in the Maximum time in the system vs the saturation density (normalised) (Figure 5.2). Although this increase can be noticed in the Average time in the system vs the saturation density (normalised) (Figure 5.1), it seem to be much less dramatic than in the non–normalised graph.

The Message processing cost vs the saturation density (Figure 5.3) yields no unexpected behaviour – as out assumptions lead to the constant £/time consumption model by the Offerings,

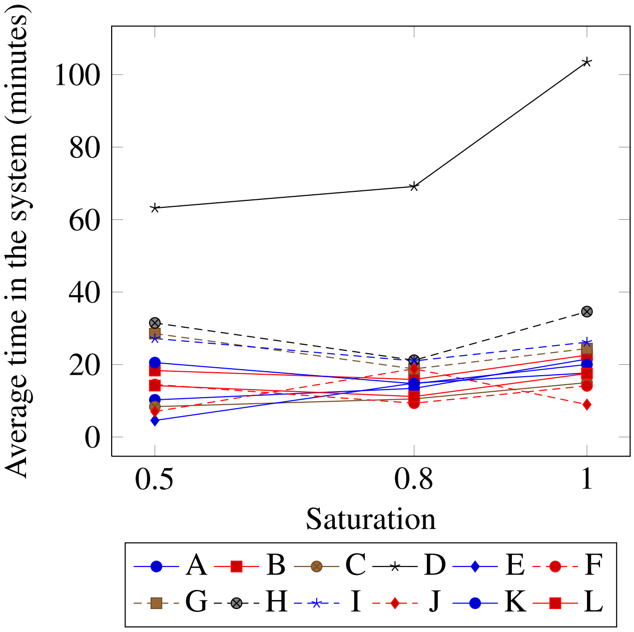


Figure 5.1: Average time in the system vs the saturation density (normalised)

the price of processing of a single message decreases, as the number of messages increases.

5.1.1 Pareto Front

As it was described in the section 3.4 “Comparison” (see page 41), strict comparison of the models had been done by finding the Offerings belonging to the Pareto front of the metrics used. All metrics except saturation density were minimised while the saturation density was maximised. Resulting table of the domination (Table 5.1) presents Pareto dominance relations for both the normalised and non–normalised results.

As noticed, in case of the non–normalised comparison, there are much more non–dominated solutions than in the case of the comparing normalised results. It is also worth noting that most Offerings (with a noticeable exclusion being the Offering I) that are dominated in the non–normalised comparison, are also dominated in the normalised mode.

Thus, the list of the non–dominated solutions is C, E, F, I, and J for the normalised, and A, C, E, F, J, K, and L for the non–normalised measurements. the non–dominated solution set represents the telehealth systems that are in any metrics no worse than any other of Offerings simulated and measured within this work.

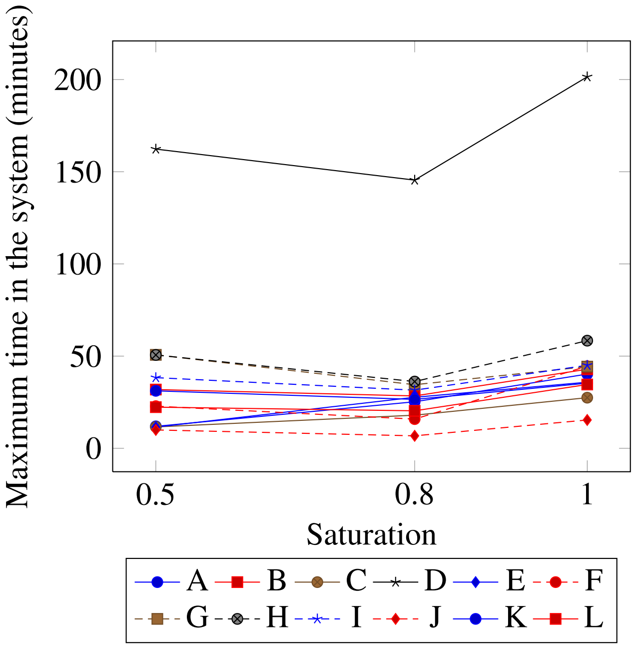


Figure 5.2: Maximum time in the system vs the saturation density (normalised)

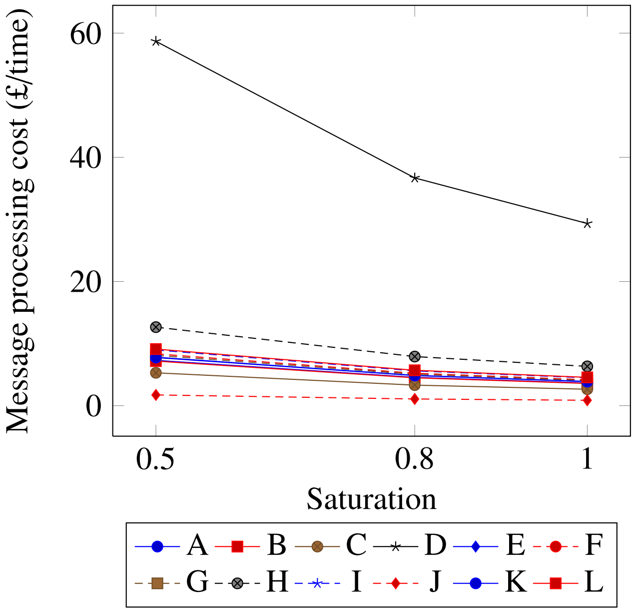


Figure 5.3: Message processing cost vs the saturation density

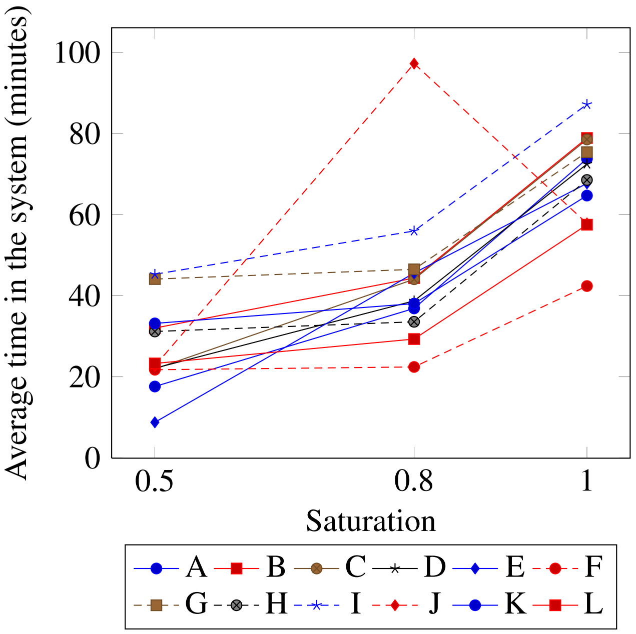


Figure 5.4: Average time in the system vs the saturation density (non–normalised)

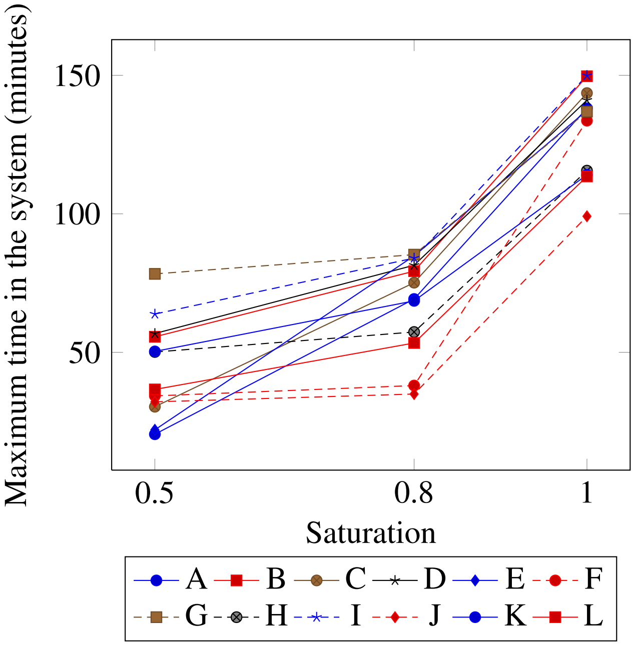


Figure 5.5: Maximum time in the system vs the saturation density (non–normalised)

Table 5.1: Offering Pareto dominance

Offering	Dominated by (normalised)	Dominated by (non–normalised)
A	C	—
B	C	C
C	—	—
D	A, B, C, E, F, G, H, I, J, K, L	F
E	—	—
F	—	—
G	A, B, C, E, K	K
H	A, B, C, E, F, I, J, K, L	L
I	—	A, B, C
J	—	—
K	C	—
L	C	—

5.2 Research Contribution

At the time of writing this work, the telehealth system design and evaluation process mostly persists outside of the academic domain of knowledge, remaining almost exclusively within the industry.

The idea of the telehealth system had been around for several decades by now, and in its modern form (a service for the general population), it holds a great promise of reducing the cost of the healthcare by increasing the efficiency of this important sector of economy. But the most of the knowledge about how to implement such a system, how to operate it, and how to measure its performance remain in an ad–hoc state within the appropriate industry.

The academic knowledge about the telehealth systems for the population remains to be very limited and scarce in the methodology, field data and the evaluation methods.

First major cornerstone contribution for this field had been made by the Adeogun et al. (2011). This work contains the data flows for twelve commercially used telehealth systems (or ‘Offerings’ in terms of that work). Given that most of the models’ properties and behaviour features, it should be possible to simulate and evaluate using the DES models, it was considered to be of benefit to initiate a research aiming to develop and refine the methodology to build and evaluate the telehealth systems.

The aim of this research was to develop a method to evaluate and compare the telehealth systems.

To use the achievements in the evaluation and comparison of the telehealth systems area the review of state-of-art was made. The results of the review and findings are stated in the chapter 2 “Literature Review” (see page 13). The chapter 2 “Literature Review” (see page 13) revealed the lack of good defined method of the telehealth evaluation and comparison. The information about the work of the existing telehealth systems is also extremely less. The most complete publication on this matter was Adeogun et al. (2011). This publication was chosen for the application of the developed method.

The next stage of this research was the proposal of the methodology to simulate, evaluate, and compare the telehealth systems. Considering that for the simulation, DES approach was chosen, the section 3.1 “Simulation” (see page 26), the section 3.2 “Building Computer DES Models” (see page 32), the section 3.3 “Evaluation” (see page 37) and the section 3.4 “Comparison” (see page 41) achieved this task.

The developed method application to the real examples of the telehealth systems was very important and necessary stage of this research. The Data Flow diagrams of the twelve telehealth systems were converted into the DES computer models using the section 3.1 “Simulation” (see page 26), the section 3.2 “Building Computer DES Models” (see page 32). The method in the section 3.1 “Simulation” (see page 26) was made to convert the Data Flow diagrams from the publication Adeogun et al. (2011) into the DES conceptual models. The method for the DES conceptual models conversion into the computer models is described in the section section 3.2 “Building Computer DES Models” (see page 32). The application of the section 3.1 “Simulation” (see page 26) to the real examples – the twelve Data Flow diagrams from the publication Adeogun et al. (2011) is described in the section 4.2 “Conceptual DES Models” (see page 43). During the simulation method application, a lot of assumptions were made about the processes in the telehealth systems. The assumptions about the telehealth systems routine are listed in the section A.1 “Simplifications Required for Model Building” (see page 119). The section A.2 “Device Usage Data” (see page 129) consists the devices usage time and speed. Information about the healthcare staff is located in the section A.3 “Staff Data” (see page 134). Using chosen metrics in the section 3.3 “Evaluation” (see page 37), the simulation results are presented in the section 4.3 “Outputs of the DES models” (see page 95).

The final stage of the research includes the telehealth systems validation and comparison. The evaluation results are listed in the section 4.3 “Outputs of the DES models” (see page 95), but the comparison is described in the section 5.1 “Simulation Results Comparison” (see page 97). Although still in the early stage, and with the applicability severely impaired by the huge number of assumptions that had to be made, the results of the developed method application are obvious and evident. The general features of the real telehealth systems are noticeable.

It is believed that this work represented a decent starting point for the academic research to improve and build upon. The assumptions are worthy enough to start researching the activities processed in the telehealth systems. The evaluation and comparison methods can also be filled up and improved. The telehealth systems optimisation is wide and a perspective area for a future research.

5.3 Research Limitations

As it had been previously mentioned, the major limitation of the current research is a huge number of assumptions in the section A.1 “Simplifications Required for Model Building” (see page 119), the section A.2 “Device Usage Data” (see page 129), the section A.3 “Staff Data” (see page 134) that had to be made to be able to construct the working DES models of the telehealth system.

Another limitation is that only DES had been performed. There are many other ways to simulate the operations of the systems (e.g. MCS, SD and ABS). Each of them can yield a new insight to the intrinsic properties of a simulated system. It would be great to build models of other types, but sadly, it could not have been done within the scope of the current work due to the financial and time limitations.

5.4 Conclusions

The aim of this work was to develop a method to evaluate and compare the existing telehealth systems.

The review of the state–of–the–art in the telehealth systems demonstrated that the development of the telehealth industry is closely connected with the development of the Information and Communication Technologies. With the help of the literature review, the possible ways to evaluate and compare the telehealth systems were introduced. To minimise investment required to study a telehealth system, a computer–aided simulation approach has been offered. However, there has been no previous work carried out that investigates the use of simulation tools to assess the telehealth systems.

The method to construct a DES model from a data flow model of the telehealth system was introduced.

Several evaluation parameters and comparison metrics have been offered. Two metrics were suggested to measure the performance of the simulated telehealth systems:

1. economic efficiency of a system (running costs per person served);
2. saturating input density (maximum volume of incoming messages that a system can server without violating maximum processing time limit)

As it is commonly is the case, the actual performance of a system is subject to a tradeoff between the domains, where it operates in (healthcare and financial). Thus, the application of the Pareto Front concept to compare telehealth systems had been introduced.

Thus the method to evaluate and compare the telehealth systems was created.

The above method had been used to construct the DES models of twelve the real life telehealth systems that were described in the Adeogun et al. (2011), to evaluate and to compare them.

The construction of the DES models, carried out by author, allowed to gain insight on parts of knowledge that have not yet been captured in the literature and therefore are viable directions for the future research.

The method to evaluate and compare the telehealth systems was developed using the four independent guidelines Pidd (2004), Robinson (2004), Banks et al. (2005), Law & Kelton (1991) and the data from other standard sources. The method was used to evaluate and compare twelve current telehealth systems. Consequently, the method and the results of the method conform to standards and thus are validated.

This work demonstrated that it is possible to build a DES model of a telehealth system knowing the data distribution flows of the telehealth system. The multitude of the future research directions was identified and listed.

5.5 Future Work

This research goal was to develop a method to compare and evaluate the telehealth systems. The research showed the limited knowledge and data in the telehealth area. Therefore, the telehealth area requires a huge volume of research. There are only few parts of the telehealth area and the lack of data affected this research.

5.5.1 Simulation Methods

The literature review has discovered that there was no research took place to investigate the use of the simulation tool to assess the telehealth systems, and the DES was chosen for this research. However, the other simulation approaches can also be applied to simulate, compare, and evaluate the telehealth systems. An implementation of the other simulation approaches can provide another set of assessments of the telehealth systems, but a combination of the few mixed assessments. The research could be supplemented with the new simulation approaches, comparison and evaluation metrics.

5.5.2 Models Building and Assumption Validation

The lack of data about the telehealth systems working routine badly affected the current work. This is the main factor of the simulation models building limits. Only one publication which provides the description of the telehealth systems working routine was found. That publication identifies the information exchange elements of the UK telehealth systems. Thus, researches devoted to the detailed and precise description of the telehealth systems information exchange routine, could be useful to fund the telehealth systems area.

The assumptions had to be made to make the building of simulation models possible. Please refer to the section A.1, section A.2 and section A.3, for the list of assumptions made during the current research considering the time and financial restrictions. In fact, every and each assumption could (and should) be validated and improved. Therefore the assumptions provide a wide field for the further researches.

It would be favourable and perspective to research the actual number of resources used in the telehealth systems to optimise the usage of resources. For example, in the subsection A.3.2, the rough assumption of the staff count has been made. A clarification of the current number or ratios of the different positions of staff in the telehealth systems can be very useful to find out the optimal count of staff in the systems, and to influence the systems' upkeep price.

The assumptions of the properties of the communication channels used to transfer, evaluate, and display the patients' tests results in the telehealth systems, also require attention. Evaluation and increase precision that assumptions are a valuable contribution, because there are many types of communication channel can be deployed in the telehealth systems – Broadband, 3G, SMS and others. Every type of communication channel has its own specifics and behaviour: SMS has an unstable delivery time, but 3G's availability is quite restricted in the UK in 2012. Therefore, a usage of each type of communication has an influence on behaviour and properties of the telehealth systems.

To dive the precise number of the healthcare professionals required to process some density of the tests results is helpful to define the time spent by each healthcare professional to analyse the patients' tests results. This is also a possible area for the further researches.

There are many assumptions for the further researches – the salaries of the healthcare professionals, the additional services of the telehealth systems modelling and others. All of them are worthy enough to be validated, specified, and improved to build more precise and close to the real life simulation models of the telehealth systems.

5.5.3 Evaluation

Some metrics to evaluate the telehealth systems were proposed in the section 3.3. Firstly, it is still an open discussion, if it is necessary to normalise the measurements results and if it is, how to do this. In current work, the normalisation is done by dividing the actual metrics with the incoming test results density. However, as seen in the Figure 5.2 and Figure 5.1, normalisation caused a slight decrease in the measurements results. It is noticeable when incoming entity density increases from 50% to 80%. The chosen metrics value does not increase so much while the incoming density increases by 30%. The normalising drives down the measurements value. This effect forces to doubt the correctness of the chosen metrics and the better normalisation ways requires a research.

Another field of research on evaluation of the telehealth systems is metrics. In this work, four metrics were introduced and used – saturation density, maximum time in a system, average time in a system, and each entity processing cost. Although these are the important metrics of the telehealth systems, other useful metrics also exist, but could not to be introduced in the current work. For example, it can be useful to measure the telehealth systems prolong life (or active life) length, average patients life length and its changing depending on telehealth system coverage and changes of the telehealth system.

5.5.4 Comparison

In current work was used Pareto ranking to compare the telehealth systems. It is possible that other ways of comparison of telehealth systems can give better results. That ways can use other metrics or weighted sum of metrics. But weighting of the metrics requires an extensive interaction with the industry and, a great amount of time and effort.

5.5.5 System Configuration

The twelve telehealth systems were modelled, evaluated, and compared in this research. As Pareto ranking had demonstrated, some of the telehealth systems can be considered superior (and some, inferior) to others. It would be of a great interest to research an ‘ideal’ system structure to improve and optimise the other systems.

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Appendix A

Assumptions

This chapter lists all the assumptions made to be able to build the models.

A.1 Simplifications Required for Model Building

Some simplifications were assumed in order to build the DES models.

A.1.1 Only Measurement Processing Process is Modelled

Relevant Offerings: A, B, C, D, E, F, G, H, I, J, K, and L

The real life telehealth system is expected to have many services: measurement submission by patients, measurement processing, a result review, and evaluation by both staff and patient.

Such system is also expected to interact with a multitude of the external systems: caregiver service, emergency healthcare service, and many others.

Plus, these days, it is also expected that a patient to be able to access his (or hers) current estimates and historical records by using the modern means of the communication such as Broadband or a smartphone.

A great amount of surrounding services, lack of study based on them and a high degree of freedom to such services can be potentially organised to make it almost impossible to construct a complete DES model of the abstract telehealth system.

Because of that, it had been decided to construct a DES model for the ‘core’ pathway only, — the process of measurement acquisition and processing by the telehealth system.

This process is assumed to end upon saving the processing results in to the device where the processing results will be available for the patient’s viewing.

A.1.2 Not Modelling Caregivers

Relevant Offerings: A, F, H, and K

The caregivers are a distinct part of the initial descriptions of several offerings discussed in this work.

Their presence is, without any doubt, important and even crucial for the operations of the system as a whole. But a description of their exact function in the grand scheme of telehealth systems' operations is virtually non-existent. Plus, it appears that they are not normally taking part in the process of measurement interpretation (their function seems to be more on the hands on side of the operations). It had been decided not to model that part of the telehealth system functionality according to the above assumption (see 'Only Measurement Processing Process is Modelled').

Thus, because of the given reasons, it had been decided not to include the caregivers to the DES models being constructed.

A.1.3 Patient Exclusive POC Devices

Relevant Offerings: A, B, C, D, E, F, G, H, I, J, K, and L

Because of the very nature of the telehealth systems, it is assumed that each patient is staying not in the centralised care facility (such as hospital), but in patients' private home. Thus, it was assumed that each patient is expected to have a private set of POC devices for serving hers (or his) needs.

A.1.4 Patient Exclusive Submission Channel

Relevant Offerings: A, B, C, D, E, F, G, H, I, J, K, and L

Because of the very same reasons described above (see 'Patient Exclusive POC Devices'), it is assumed that patients will have the personal, independent Internet/Phone/SMS connections, and the submission of one patient's results cannot influence the submission of other patients' result at the sender's (patients') end.

A.1.5 Single Inbound Gateway on the Telehealth Centre Side

Relevant Offerings: A, B, C, D, E, F, G, H, I, J, K, and L

Although it is assumed that each patient has its own, independent means of submitting the results to the hospital (see ‘Patient Exclusive Submission Channel’), the hospital itself is assumed to have one and only gateway that all messages arrive to.

Of course, this is not always the case in the real world, it is possible to have several phone numbers for receiving of SMS formatted results, several Internet connections for receiving a high volume of results through the Internet, and one can have a cluster of result processing servers to be able to process a huge number of patient results simultaneously.

Nevertheless, for the initial construction of a model, all these possibilities are intentionally left outside of a model. Their introduction is one of the proposed directions for a future research.

A.1.6 Bandwidth Limited Result Entry

Relevant Offerings: A, B, C, D, E, F, G, H, I, J, K, and L

It is assumed that no matter what channel and hardware patient is using to submit his (or hers) results to hospital, the computational capabilities of a device patient is using to submit these results, greatly surpass the requirements inflicted by the submission of these results.

However, the bandwidth of a channel used for submission is still considered.

A.1.7 Single Measurement Handling Path

Relevant Offerings: A, B, D, E, G, and J

Each measurement (or a set of measurements) passes through several stages in the telehealth system: transmit, automated evaluation, human–aided evaluation, and act result storage. Usually there are several alternatives to how each of these stage can be handled. For example, transmission can be done via PC (Broadband), SMS, and Phone.

It is assumed that passing through one and only type of a handling procedure is sufficient for the result processing to advance to the next stage of processing chain.

A.1.8 PC Preference for Measurement Entry

Relevant Offerings: A, B, D, and E

Because PCs commonly have a much more wide selection of available I/O interfaces, one can assume that using them for result acquisition and submission to the telehealth systems will be more widespread.

It is also expected for health professionals to prefer PCs for receiving alert (and the result review is expected to be done via PC exclusively).

In the models described, it was assumed that PC will be used with a 70% probability (and mobile phone will be used with remaining probability of 30%).

A.1.9 Automatic Initial Processing

Relevant Offerings: A, B, D, E, F, G, H, I, J, K, and L

It is assumed that the receipt and the initial processing of results can be carried automatically, otherwise, the benefits of introducing the telehealth systems instead of classical hospital systems are uncertain.

A.1.10 Most Appropriate Means of Communication Assumed

Relevant Offerings: A, B, C, D, E, F, G, H, I, J, K, and L

There are data flow path ways in the used Data Flow diagrams, that do not define a medium of communication between the entities such as EPR and PC or MP.

If not explicitly stated in the data flow diagram source, the following communication medium is assumed:

- 3G connection for the communication with MP
- Broadband connection for Internet access – both for patient and for an institution
- LAN connection for PC to PC communication within the healthcare institution

A.1.11 Alert Sending is an Explicit Action

Relevant Offerings: A, B, D, E, F, G, H, I, K, and L

In some models used, the alerts are an implicit feature of the communication between the health professional and computerised processing system.

Due to the nature of DES systems, this functionality has to be explicitly implemented in DES models.

A.1.12 Test Result Interpretation is Simple Activity

Relevant Offerings: A, B, D, E, F, G, H, I, J, K, and L

In real life, a process of result interpretation involves many subs–activities: result acquisition from a computer storage system, result review, assessment, and a possible patients' record update.

Due to the granularity of data available for the described models, it does not seem to be viable to represent all these sub–activities in a DES model.

Thus, it was decided to represent the whole process described above as a single action in models simulated within the boundaries of the current work.

A.1.13 Priority of Unexpected Results

Relevant Offerings: A, B, D, E, F, G, I, K, and L

As modelled systems are meant mainly for a chronic condition monitoring, there are 'expected results', values of the measurements that patients are expected to yield given that they are following the lifestyle guidelines.

This brings a set of 'unexpected results' in to existence – results that are abnormal given patients' state of health and history. Such results are ought to be handled as having a higher priority than 'expected results' by the health professionals.

A.1.14 Automated Processing Results Ends on Sending of an Alert

Relevant Offerings: A, B, D, E, F, G, I, K, and L

In most systems, when the automated entity result processing notifies the health professionals of unexpected patient's results, a massage is sent to the health professionals' PC or MP.

It is assumed that given notification happens in the form of sending an e–mail (or SMS respectively) to a health professional's account.

A.1.15 Probabilistic Unexpected Results

Relevant Offerings: A, B, D, E, F, G, H, I, J, K and L

Many telehealth systems divide patients' results in to the two classes – expected and unexpected.

‘Expected’ results are results that are expected for given the current patients’ state and health. While the ‘unexpected’ results are the ones that are outside of the pre-determined patients’ norm.

It was decided to simulate the ‘unexpected’ results by marking 5% of the incoming patients’ results as unexpected.

A.1.16 Electronic Patient Record System is Fast

Relevant Offerings: A, B, C, D, E, F, G, H, I, J, K, and L

It is assumed that a computer system used by the health personnel to access the test results is robust and fast enough, not to have a major influence on the performance of a telehealth system as a whole.

Thus, it was decided not to include a model of I/O limitations the telehealth system may have when it comes to accessing of results by a personnel.

A.1.17 Technology is Cheaper Than Professionals

Relevant Offerings: A, B, C, D, E, F, G, H, I, J, K, and L

It is assumed that each health professional has the individual resources required for the interpretation of test results. Thus, there are no queues for accessing these resources by the health professionals.

A.1.18 Order Insensitive Measurement Sessions

Relevant Offerings: B and D

Some chronic conditions require several POC devices to be used in combination. Assumption was made that patients use their POC devices in a consecutive order, with each device being used every time when a patient has a measurement session. Thus, it is assumed that the order of using available POC devices is not of importance, and can be left outside of the simulations performed.

A.1.19 Equal Chronic Condition Distribution

Relevant Offerings: B, C, D, F, G, H, I, J, K, and L

Table A.1: A list of assumptions applied to the Offerings (Part 1)

Offering Assumption	A	B	C	D	E	F	G	H	I	J	K	L
Only Measurement Processing Process is Modelled (page 119)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Not Modelling Caregivers (page 120)	✓					✓		✓			✓	
Patient Exclusive POC Devices (page 120)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Patient Exclusive Submission Channel (page 120)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Single Inbound Gateway on the Telehealth Centre Side (page 120)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Bandwidth Limited Result Entry (page 121)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Single Measurement Handling Path (page 121)	✓	✓		✓	✓		✓			✓		
PC Preference for Measurement Entry (page 121)	✓	✓		✓	✓							
Automatic Initial Processing (page 122)	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Most Appropriate Means of Communication Assumed (page 122)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Alert Sending is an Explicit Action (page 122)	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓
Test Result Interpretation is Simple Activity (page 123)	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
Priority of Unexpected Results (page 123)	✓	✓		✓	✓	✓	✓		✓		✓	✓
Automated Processing Results Ends on Sending of an Alert (page 123)	✓	✓		✓	✓	✓	✓		✓		✓	✓
Probabilistic Unexpected Results (page 123)	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓

Some of the simulated telehealth systems are able to monitor several chronic conditions simultaneously.

This is considered important, as the actual patients' condition affects the list of actual POC devices the given patient will be using.

It was assumed that in the case of telehealth system, monitoring several conditions, probability distribution of given conditions will be equal, so there is an equal chance for any condition dependant POC devices set to be invoked.

A.1.20 The Probability Division Between Entering Devices

Relevant Offerings: B, E, G, H, J, and L

In some models, there are devices called the 'entering devices': they act as a relay between the POC devices and telehealth systems' servers. Sometimes, a model features several of these devices (e.g. PC, MP, etc).

As a simplification, it was assumed that the actual device to be used is determined at random with equal probability for each and every entry device.

The similar assumption is also used for every another part of the systems, if the selection is required. The assumption A.1.8 regulates the selection between MP and PC.

A.1.21 Health Professionals Consult Each Other on Unexpected Result Receive

Relevant Offerings: E, H, I, and L

In some models, there are several types of health professionals (e.g. GP and speciality doctors) that noted to be interacting with each other. But it is not defined under what circumstances they are engaging in the given interaction. It was assumed that such interaction is taking place only upon receiving of an unexpected result, and it does not happen when a GP is reviewing a result that had not been marked as unexpected.

A.1.22 Entity Processing Ends on Result Storage

Relevant Offerings: A, B, C, D, E, F, G, H, I, J, K, and L

As the telehealth system is essentially a remote health monitoring system, it is vitally important for patients to be able to receive a feedback on results they are submitting.

Table A.2: A list of assumptions applied to the Offerings (Part 2)

Offering Assumption	A	B	C	D	E	F	G	H	I	J	K	L
Electronic Patient Record System is Fast (page 124)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Technology is Cheaper Than Professionals (page 124)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Order Insensitive Measurement Sessions (page 124)		✓		✓								
Equal Chronic Condition Distribution (page 124)		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓
The Probability Division Between Entering Devices (page 126)		✓			✓		✓	✓		✓		✓
Health Professionals Consult Each Other on Unexpected Result Receive (page 126)					✓			✓	✓			✓
Entity Processing Ends on Result Storage (page 126)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Therefore, an assumption was made that result entity processing ends when it can logically stored on the result storage device (e.g. a computer server), that has potential to serve a feedback to the patients.

For example, when patients access a web service running on a given result server.

Table A.3: POC device deployment vs condition

	Glucometer	Blood pressure (BP) Monitor	ECG monitor	Weighting Scale	Peak flow meter	Pulse Oximeter	Coagulation meter	All–in–one monitor	MiniClinic	Professional ECG monitor	Vital Signs Monitor	Temperature Probe
Diabetes[1]	✓											✓
Hypertension[2,a]		✓	✓				✓					✓
Chronic heart failure[3]		✓	✓	✓			✓					✓
COPD[4]					✓	✓		✓	✓		✓	✓
Asthma[5]					✓						✓	
Stroke[6]		✓	✓			✓	✓					✓
CHF[7]		✓	✓	✓			✓	✓	✓	✓	✓	✓
Cardiac diseases		✓	✓	✓				✓	✓	✓		
Respiratory diseases								✓	✓			

Relevant publications:

[1] New York State Department of Health (2008), Sanchez-Alavez et al. (2009)

[2] Costa M.A. (2009), *What is High Blood Pressure?* (2012), Bauer (2011)

[3] *Heart Failure - NHS Choices* (2010), A. Chen (2012), Simon (2011), *What is High Blood Pressure?* (2012), Bauer (2011)

[4] Schiffman (2009), Pruitt MBA (2010)

[5] Bass (2011)

[6] Wedro (n.d.), *What is High Blood Pressure?* (2012), Bauer (2011)

[7] *Congestive heart failure definition - Heart Disease and Other Cardiovascular Conditions on MedicineNet.com* (2012), A. Chen (2012), Simon (2011), *What is High Blood Pressure?* (2012)

Notes:

[a] Also known as high blood pressure

A.2 Device Usage Data

The specific timings were required in order to simulate the DES models.

As DES models require for various model element usage, timings to set for simulation to execute correctly, for results described in the current work to be replicable, verifiable and falsifiable, values used in the described simulations (chapter 4) are provided below.

A.2.1 Point–of–Care Devices (POC Devices)

A reasonable attempt to make given values as realistic as possible had been made, but due to the utter lack of information, an average usage time of number of devices, empirical guesses have been made for the usage time of the devices that the author was unable to find statistical information for.

For the devices that only have the average usage time available, but to minimum or maximum time, these times were set to ±20% of the average usage time.

Glucometer

Used timings (min, avg and max): 10.0, 12.5 and 15.0 minutes.
Manzella (2006) mandates that time required is “10 to 15 minutes”, therefore minimum time is set to 10 minutes, maximum to the 15 minutes and average to the $\frac{10+15}{2} = 12.5$ minutes.

Weighting Scale

Used timings (min, avg and max): 4.00, 6.00 and 8.00 minutes.
According to Nikolai (n.d.), measuring one’s weight properly requires several distinctive steps to be taken in a particular order. Considering that people using the telehealth systems are likely to experience body movement problems, it is reasonable to expect body weighting process to take between 4 and 8 minutes.

Blood Pressure Monitor (BP Monitor)

Used timings (min, avg and max): 15.0, 17.0 and 19.0 minutes.
As is described in familydoctor.org editorial staff (n.d.), using a Blood pressure monitor (BP Monitor) requires for patient to rest before performing the actual measurement. Thus, the measurement process is fairly lengthy (15—19 minutes).

Coagulation Meter

Used timings (min, avg and max): 3.00, 4.00 and 6.00 minutes.

Although the measurement itself takes seconds, it is required to have certain preparations beforehand (e.g. wash one's hands), Braeuner (2011). Thus, the whole process is expected to take between 3 and 6 minutes.

Electrocardiogram Monitor (ECG Monitor)

Used timings (min, avg and max): 13.0, 15.0 and 17.0 minutes.

According to the Reviewer Robert J Bryg (2009) "It takes about 10 minutes to attach the electrodes and complete the test, but the actual recording takes only a few seconds.". As it is required to undress beforehand, the total time of usage is expected to be between 13 and 17 minutes.

Pulse Oximeter

Used timings (min, avg and max): 5.00, 6.00 and 7.00 minutes.

Although the measurement takes only few seconds, it is necessary to remove nail polish from nails (Esther (2010)). Entering of results into the telehealth system also takes time, thus, a total time is expected to be between 5 and 7 minutes.

Peak Flow Meter

Used timings (min, avg and max): 3.00, 5.00 and 8.00 minutes.

A Peak flow meter performs its measurement in a breath's time (*How to use your peak flow meter: MedlinePlus Medical Encyclopedia* (2010)). But it is necessary to calm one's breath beforehand, and to enter the measurement results afterwards. Hence, the timing between 3 and 8 minutes.

All–in–one Monitor

Used timings (min, avg and max): 16.3, 20.4 and 24.5 minutes.

This device can be found on the Figure 4.13 "Data Flow Diagram for the Offering D" (see page 59), and as seen from the clarification note there, the 'All–in–one monitor' is a device that provides several sets of results: pulse, BP, breathing rate, temperature, heart rate, heart rhythm, Electrocardiogram, and blood oxygen level measurements.

Considering that it would make sense to perform all these measurements simultaneously, it is reasonable to expect for the All–in–one monitor usage to consume at least as much time as it takes to use the most time consuming POC device it replaces. That is, BP Monitor with an average usage time of 17 seconds. 20% overhead had been added to the timing of a BP Monitor, as the whole test set is likely to take a bit more time than a single test, as patient has to connect more sensors.

Professional ECG Monitor

Used timings (min, avg and max): 6.00, 7.50 and 9.00 minutes.

According to Ross (2012), the usage time of a professional Electrocardiogram monitor (ECG monitor) is 5–10 minutes. The value in the middle of a given period was used: 7.5 minutes (or 450 seconds).

MiniClinic

Used timings (min, avg and max): 0.400, 0.500 and 0.600 minutes.

According to the A Medic4all Group Company (2012), the MiniClinic device is a wristwatch type of device that is constantly monitoring the patient's condition with an automatic data transmission feature. It was assumed that it takes half a second for this device to discover a result submission gateway and to submit data through it.

Vital Signs Monitor

Used timings (min, avg and max): 0.400, 0.500 and 0.600 minutes.

Usually, the vital signs monitor is a persistent service just like the MiniClinic.

Temperature Probe

Used timings (min, avg and max): 4.00, 5.00 and 6.00 minutes.

According to Halligan (2011), it takes about five minutes for a glass thermometer to get to a thermal equilibrium with patient's body.

Generic Device

Used timings (min, avg and max): 0.400, 0.500 and 0.600 minutes.

There are several devices described in the original publication that cannot be traced to their designs in the real world. For example, “Telehealth Monitor 1A”, “Telehealth Monitor 1B”, and “Telehealth Monitor 2” in the Offering B Figure 4.5 “Data Flow Diagram for the Offering B” (see page 50).

Being unable to determine the actual time it takes to interact with these devices, the author decided to accept an empirically feasible value of 30 seconds.

A.2.2 Data Processing and Transmission

For all patients' home–to–telehealth servers' data transmission timings, it was assumed that patients' results to be transmitted are 2 kB in size plus the overhead of time it takes to establish is a TCP/IP connection of 0.2 s.

For accessing the processed results (both by a personnel and patient), when done with the aid of a computer or smartphone over the network, causes 320 kB to be downloaded (this number is taken from Google's estimate of an average size of page on the Internet Ramachandran (2012)). In addition, it is assumed that this Web page consists of eight resources, each of which requires a separate Hypertext Transfer Protocol (HTTP) connection to be made with respective 0.2 s overhead for each connection (as HTTP is served over TCP/IP protocol).

Result Entry Time Using PC

Used timings (min, avg and max): 0.0160, 0.0200 and 0.0240 minutes.
It is assumed that it takes 0.02 minutes ($\approx$1.2 seconds) for a PC to receive a result from a POC device, format it and schedule it for transmission to the telehealth system's server.

Result Entry Time Using Mobile Phone

Used timings (min, avg and max): 0.0240, 0.0300 and 0.0360 minutes.
It is assumed that it takes 0.03 minutes ($\approx$1.8 seconds) for MP to receive a result from POC device, format it and schedule it for transmission to the telehealth systems' server.

Result Transmission Using Serial Port

Used timings (min, avg and max): 0.185, 0.231 and 0.277 minutes.
A serial port had been used for transmitting data since the computer technology had been in its infancy.

There is a stellar amount of transmission speeds (measured in bit s^{-1}) serial port can operate at: 2400, 4800, 9600, 19200, 38400, etc.

9600 bit s^{-1} had been chosen as the most widespread and 'classic' speed lots of equipment operates by default (e.g. Arduino).

Result Transmission Using Infrared Port

Used timings (min, avg and max): 0.002 72, 0.003 39 and 0.004 07 minutes.
The infrared communication is a widespread way of transmitting data that had been only a de–facto standard for transmitting the data wirelessly before Bluetooth 2.x arrived.

4 Mbit s^{-1} seems to be a standard speed for the modern hardware. Clarinet Systems (2012), ByteRunner technologies (2012)

Result Transmission Using USB

Used timings (min, avg and max): 0.002 67, 0.003 33 and 0.004 00 minutes.
There are three revisions of USB standard in the existence as of year 2012: 1.x, 2.0 and 3.0.

With version 1.x being largely out of production, and 3.0 only starting to appear on the market, it was assumed that POC devices are likely to be using a USB standard version 2.0 that provides 35 Mbit s^{-1} effective bandwidth (ThinklogicalTM 2012, page 1).

Result Transmission Using Bluetooth

Used timings (min, avg and max): 0.002 76, 0.003 45 and 0.004 14 minutes.
As of year 2012, there are four versions of Bluetooth standard: 1.x, 2.x, 3.0 and 4.0.

The version 1.x consists of two major Bluetooth stack releases: 1.0 and 1.1. Version 1.0 had never been widely used due to the numerous bugs in the standard, while version 1.1 had been quite popular but its popularity is diminishing now. 3.0–enabled devices just begin to appear and there are no devices that use 4.0 stack.

As for now, the most widespread Bluetooth stack of version 2.x. According to *Bluetooth 2 - Enhanced Data Rate (EDR) :: Radio-Electronics.Com* (2012), Bluetooth SIG (2004), usable data channel width is approximately 2.1 Mbit s^{-1}.

Result Submission Via the Internet

Used timings (min, avg and max): 0.002 69, 0.003 36 and 0.004 03 minutes.
According to the Ofcom (2011*a*), the average Internet connection speed in the UK is 7.5 Mbit s^{-1}

Result Submission Via 3G Mobile Network

Used timings (min, avg and max): 0.002 76, 0.003 46 and 0.004 15 minutes.
According to the Ofcom (2011*b*), UK 3G broadband speed is 2.1 Mbit s^{-1}, falling to an average of 1.7 Mbit s^{-1} during the peak evening period of 8.00 pm to 10.00 pm. It was decided to use the average 1.9 Mbit s^{-1} of these numbers for simulation.

Result Submission Via GPRS

Used timings (min, avg and max): 0.008 76, 0.0109 and 0.0131 minutes.
According to *What is GPRS (General Packet Radio Service)?* (2012), normally GPRS con-

nection provides communication speeds about 32 kbit s^{-1} to 48 kbit s^{-1}. The middle value of 35 kbit s^{-1} is used.

Evaluation Result Access Via LAN

Used timings (min, avg and max): 0.0137, 0.0171 and 0.0205 minutes.
The common LAN speeds are: 10 Mbit s^{-1}, 100 Mbit s^{-1} and 1000 Mbit s^{-1}. With the oldest technology being largely phased out almost everywhere, and the lack of economic sense in the updating 100 Mbit s^{-1} LANs to 1000 Mbit s^{-1} standard, the most common speed used for wired LAN networks is 100 Mbit s^{-1}.

Assuming that Intranet LAN web access is delivered with 100 Mbit s^{-1} LAN connection.

A.2.3 Misc Timings

Server Hardware Limitation

Used timings (min, avg and max): 0.008 00, 0.0100 and 0.0120 minutes.
In the real world, computers (even expensive corporate grade servers) have their limits when it comes to the information processing. These limits arise because of the various reasons, Hard Disk Drive (HDD), Random Access Memory (RAM) and Central Processing Units (CPUs) are all having their appropriate I/O limits.

For the simplicity's sake (and because of the lack of a prior knowledge of what hardware is going to be used in any particular telehealth system installation), the limits used in simulations performed were chosen on the empiric expectation of the performance of a complex software: server is expected to be able to handle 550 connections simultaneously (with any remaining connections being placed in a queue) and a single result processing is expected to take 0.01 minute (≈0.6 seconds).

A.3 Staff Data

To build a working DES model, it is necessary to decide on the number of acting entities in it. This means that it is necessary to decide on types and numbers of personnel to be modelled.

Description of the models in Adeogun et al. (2011) includes several interchangeable and non official terms on various levels of a semantic abstraction.

The relevant hierarchy of terms is:

1. Practitioner of medicine *American Heritage Dictionary Entry: Clinician* (2012).

   Synonyms:

- Clinician
- Healthcare professional
- Health professional

(a) Nurse

(b) Doctor

Synonyms:

- Physician

i. Specialist doctor (a doctor who is an expert in his/her narrow area)

Synonyms:

- Specialist
- Expert

ii. General Practitioner *American Heritage Dictionary Entry: general practitioner* (2012)

It is worth noting that the Offering D features “Cardiology expert” in the data flow, and this position is officially named “Speciality doctor in Cardiology” and is assigned to its respective pay grade.

It had been decided to assume that all non–specialist doctors should be considered GPs in all models unless it is explicitly stated that given entity is a Speciality Doctor (e.g. “Cardiology expert”). Thus all “Clinician” and “Physician” positions are considered to be GP in the current work.

A.3.1 Salaries

To calculate the cost of running of a telehealth system, it is necessary to define the salaries of staff recruited in to the system. Please refer to the Table A.4(see page 136) for the list of salaries used within the current work.

A.3.2 Head Count

It is very difficult to make an estimate of size of the staff required by the hypothetical telehealth system.

As a starting point, it was decided that the count of various staff type in a telehealth system should be related to respective staff types in total NHS staff count.

Table A.4: Staff Salaries

Position	Salary (£, per annum)
GP	109,400[1]
Nurse	24,401[2]
Specialist nurse	29,859[3]
Speciality Doctor	69,000[4]

References:

[1] The NHS Information Centre, Workforce & Facilities (2011)

[2] (NHS 2012, Band 5 average)

[3] (NHS 2012, Band 6 average)

[4] (The NHS Information Centre, Workforce Analysis Team 2010, page 10)

Table A.5: NHS total of employed health professional count in 2011

Position	Total NHS head count	Name in the source document
GP	39,409	
Nurse	370,327	Total qualified nursing staff
Specialist Nurse	14,018	Other doctors in training and equivalents
Speciality Doctor	12,223	Other medical and dental staff

Data is acquired from (Health and Social Care Information Centre, Workforce and Facilities Team 2012, Table 1a)

Table A.6: Staff head count used in DES models

Position	Count
GP	13
Nurse	26
Specialist Nurse	5
Speciality Doctor	4

The NHS employed the following number of health professionals in the year 2010 (see Table A.5 on page 136). As seen, the number of employed Nurses dwarfs the number of other employees. It is authors' belief that this is because of a wide range of the manual labour services the nurses are involved in – patients care, doctors' assistants, helping the elderly patients and others. Because of that, it had been considered that the NHS nurse statistics is not directly applicable to the case of a telehealth institutions and services.

It had been noticed that call centre[1] industry has a similar functionality and thus, should have a similar workforce distribution. According to the (CfA business skills @ work 2012, Page 12, Table 1), it is reasonable to expect for call centres to have 17% and 36% of its staff to be experienced, and inexperienced customer service advisers respectively. As role of the nurses and GPs in a telehealth centre are considered to be reasonably similar to the customer service advisers, it had been assumed that a telehealth centre should employ GPs and nurses in the similar ratios. As $17 \times 2 \approx 36$, it was decided that the number of nurses is always twice the number of GPs.

Of course, the total NHS doctor numbers represent the total number of people required to serve the whole population of UK. To scale them down to a reasonable size, an estimate of an hypothetical telehealth system, it was decided to calculate an average number of health professionals required by the NHS to serve 20,000 persons in UK, as it is the size of a small town. It is expected that a single telehealth centre to be able to cover a town with its services.

As the estimated population of UK in 2010 is 61,792,000 people, Office for National Statistics (2011*b*) this is the most recent population estimate available as of the summer 2012, and this is the reason why the 2010 NHS statistics was used, instead of the already available numbers for year 2011.

Thus, to calculate a total head count to be used in the DES simulation, it was decided to scale the total staff head count down to the number of employees supposedly required to serve 20,000 UK citizens. Given the total UK population disclosed above, the computation formulae turns out to be $\frac{X}{61792000} \times 20000$. The actual staff count used in the models can be seen in Table A.6 (see page 137).

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[1] Sometimes also referred to as 'quitline'.

Appendix B

AnyLogic Models

In order to complete the research's conclusion, it was decided to include the AnyLogic model diagrams that were used to simulate the given telehealth systems.

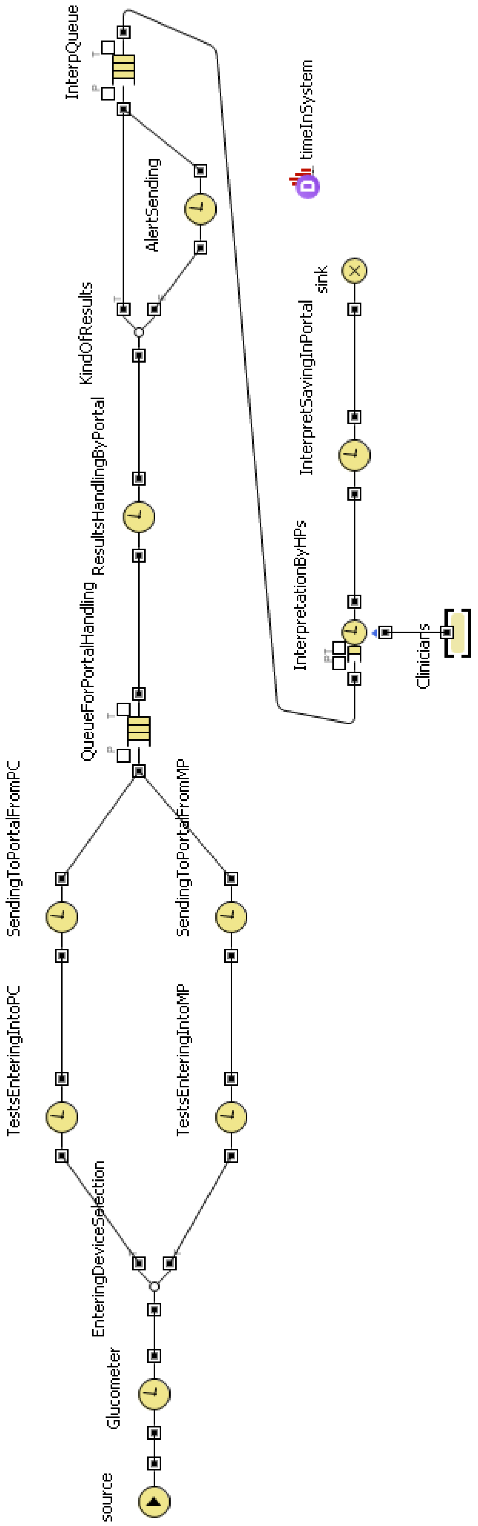

Figure B.1: AnyLogic model for the Offering A

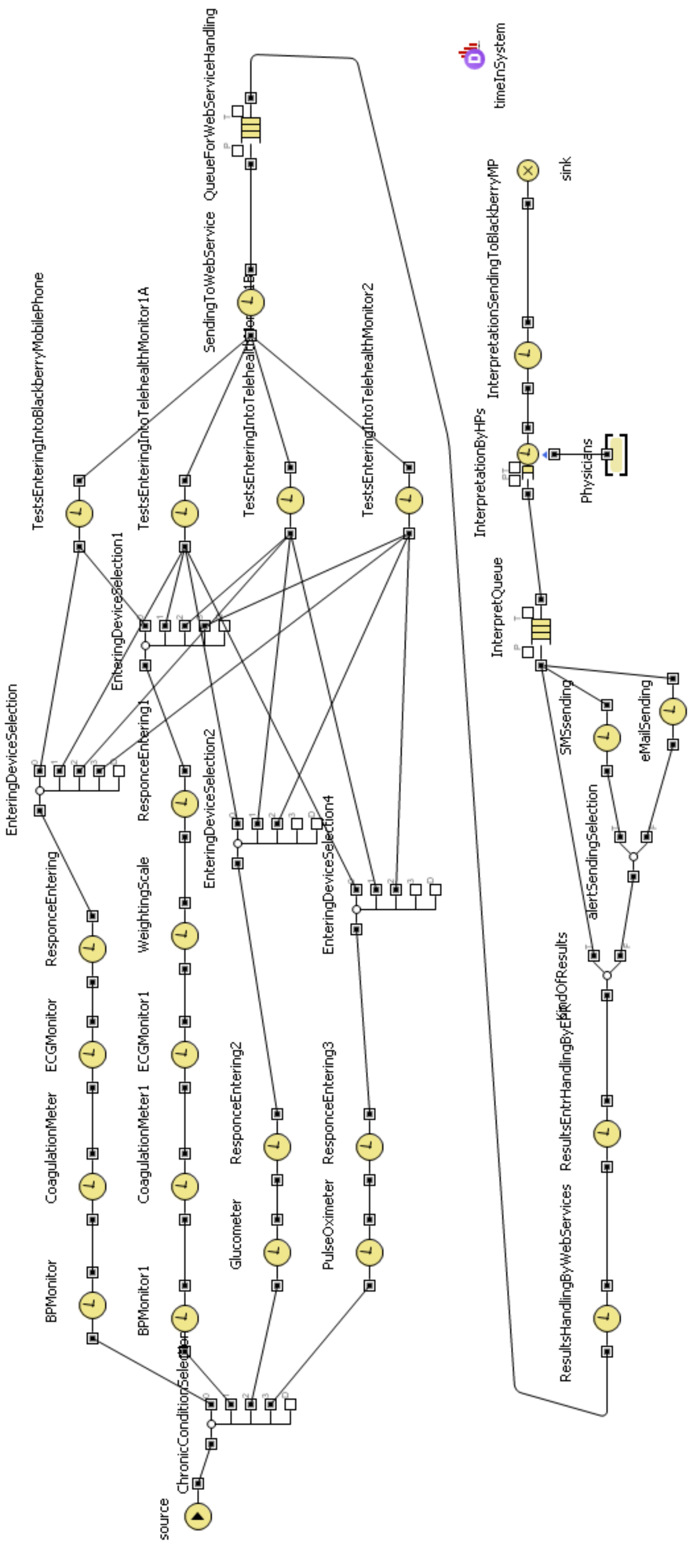

Figure B.2: AnyLogic model for the Offering B

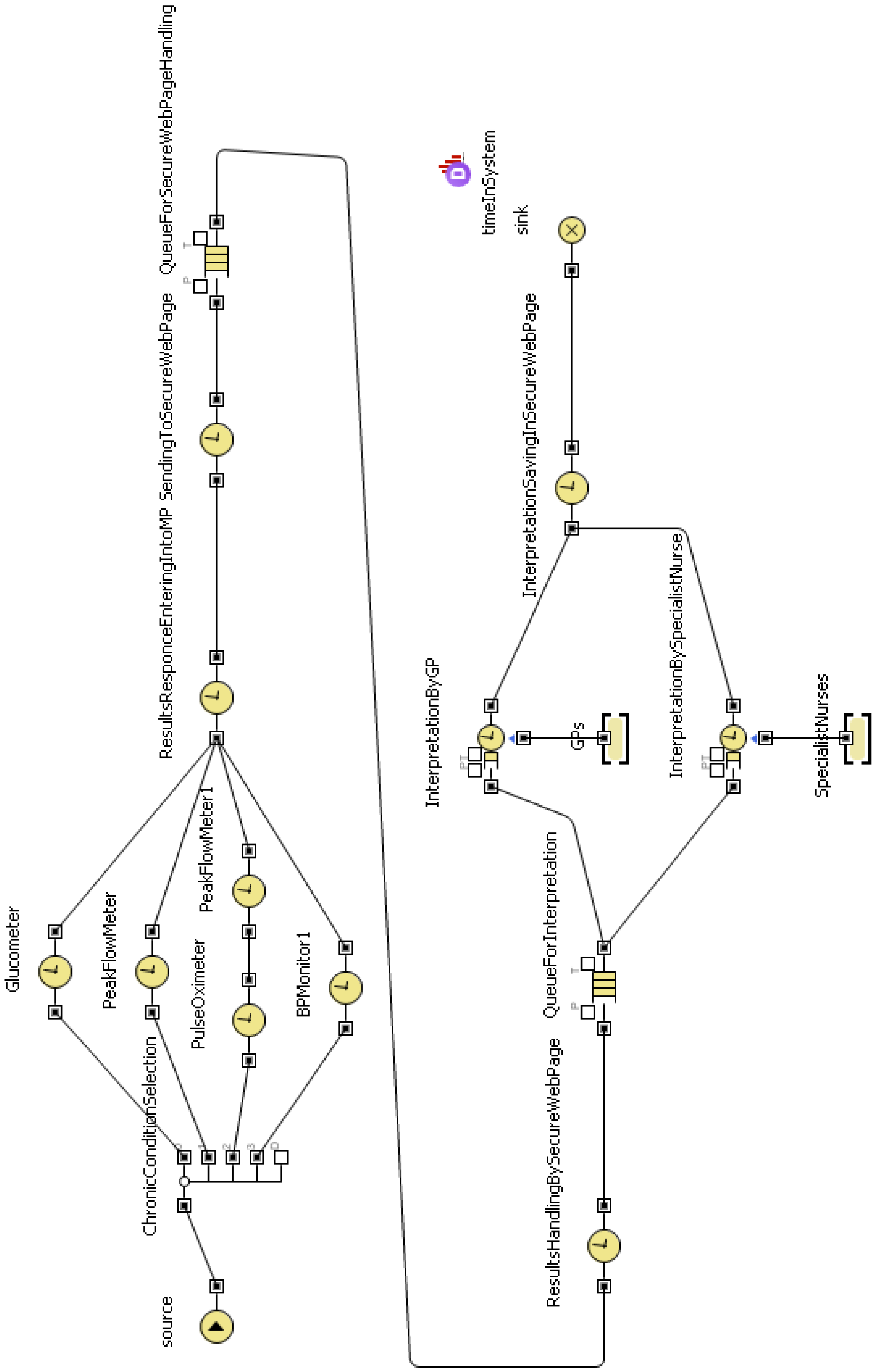

Figure B.3: AnyLogic model for the Offering C

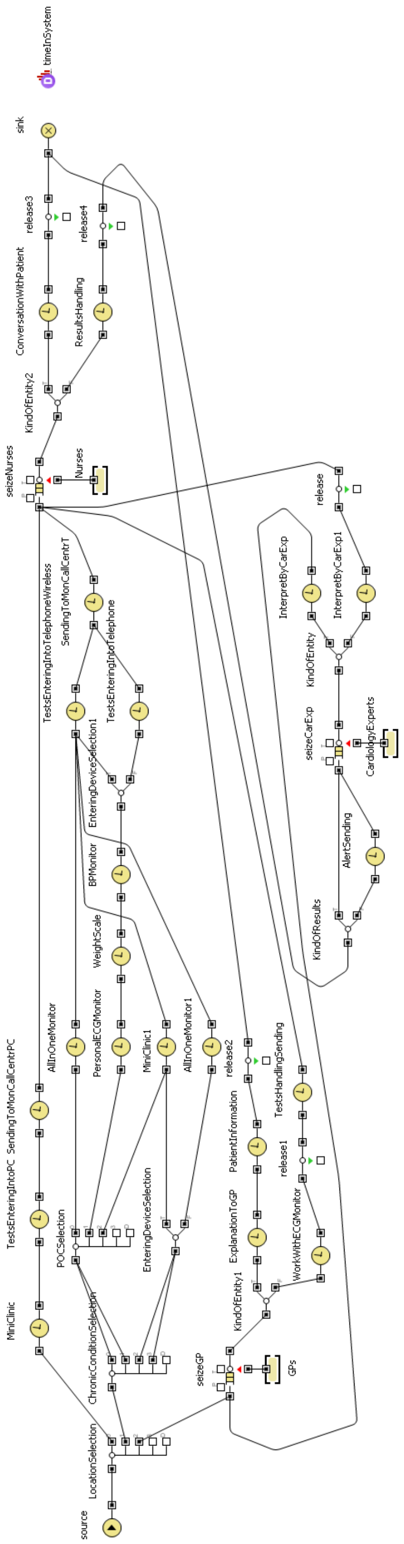

Figure B.4: AnyLogic model for the Offering D

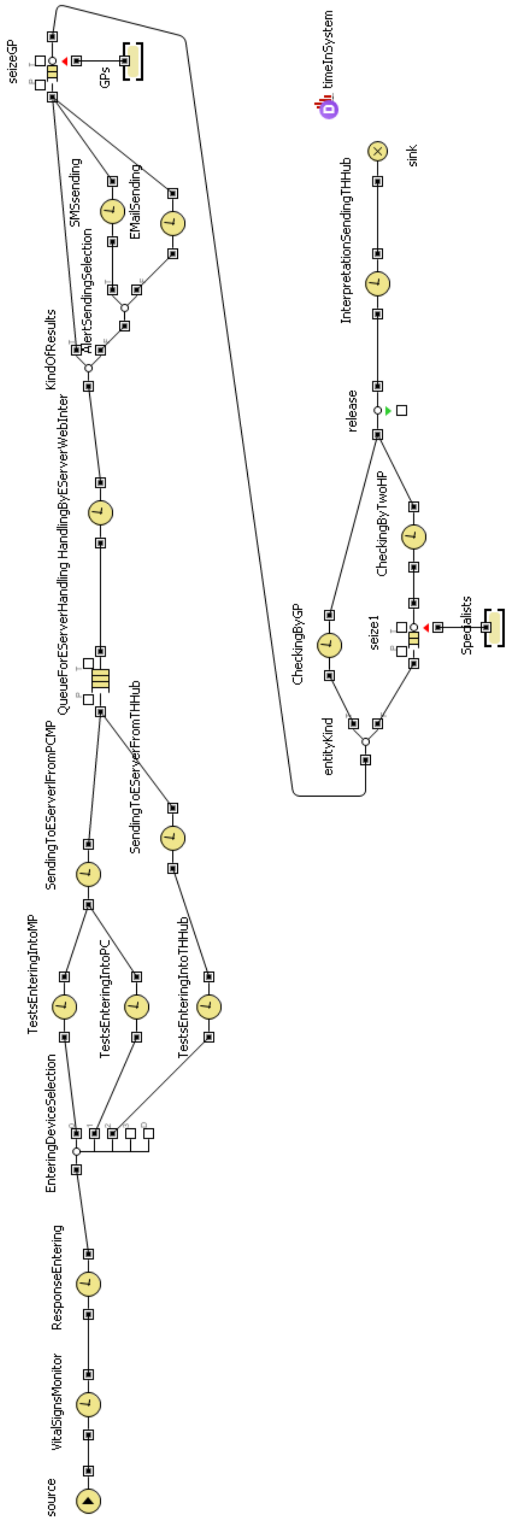

Figure B.5: AnyLogic model for the Offering E

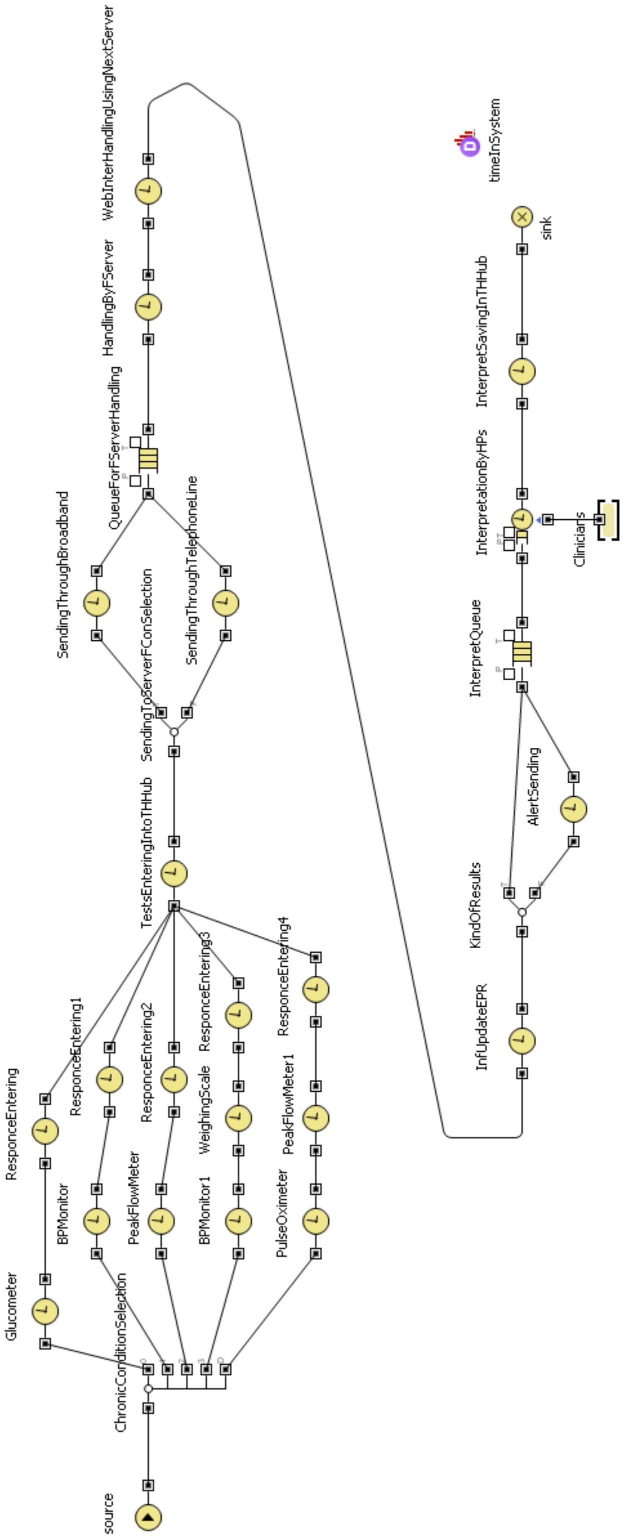

Figure B.6: AnyLogic model for the Offering F

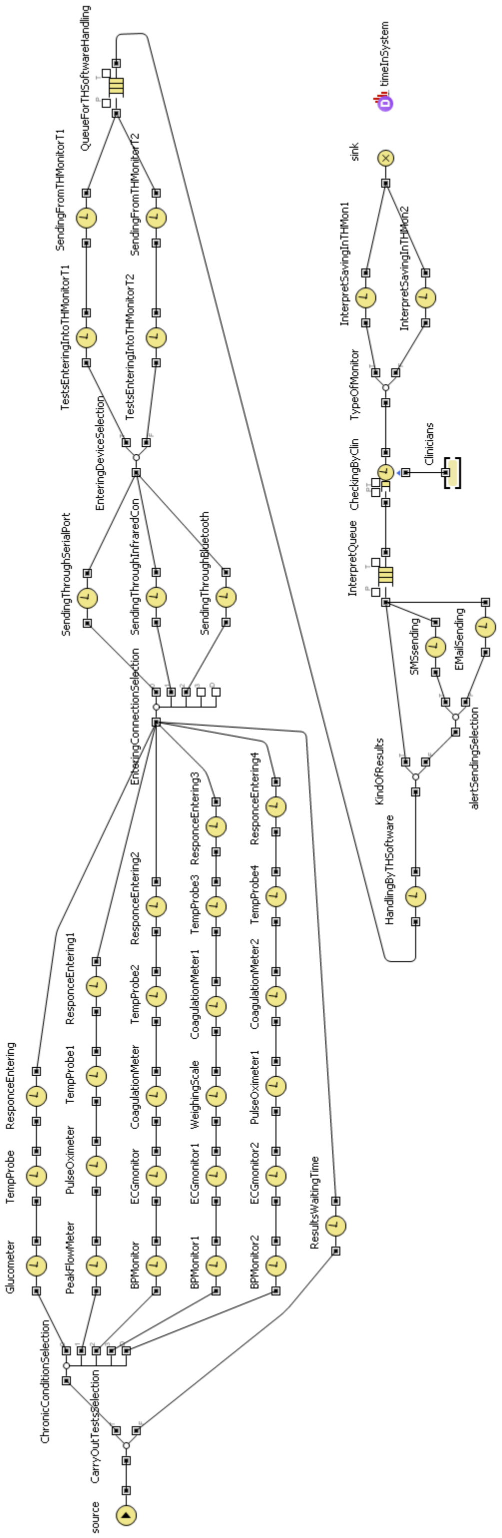

Figure B.7: AnyLogic model for the Offering G

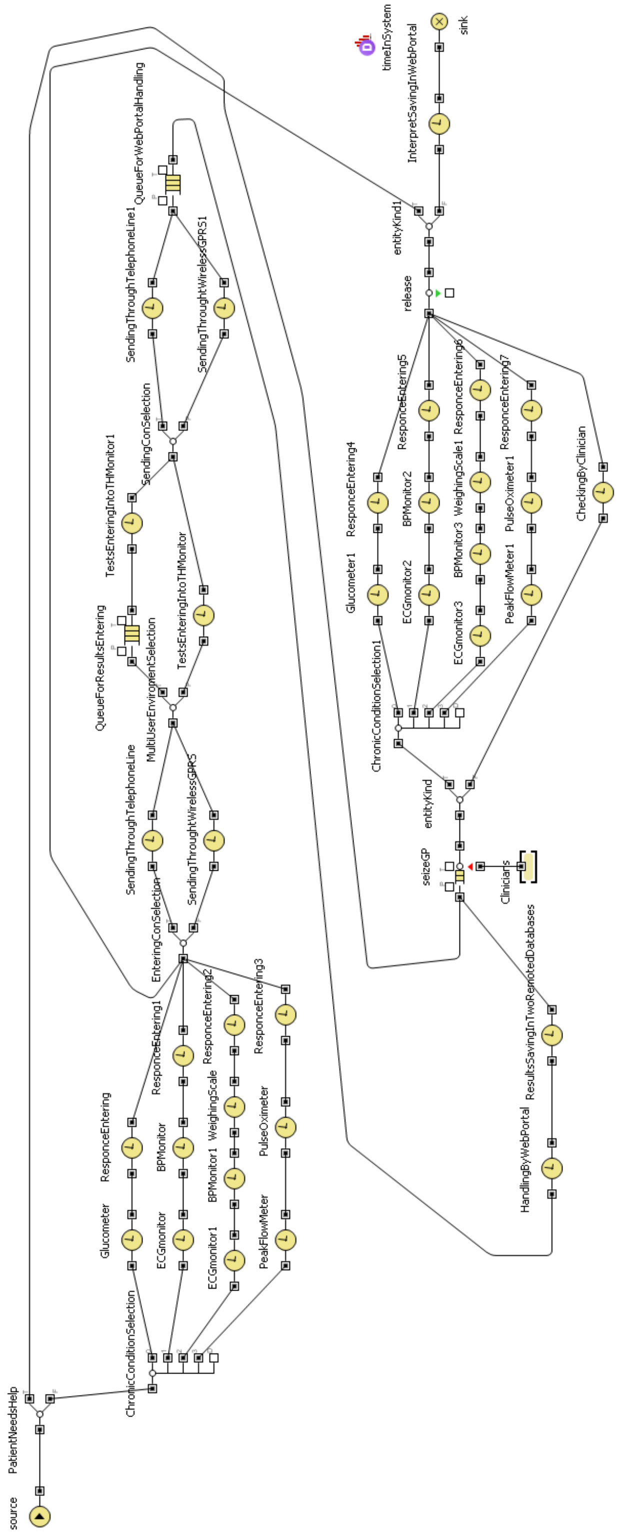

Figure B.8: AnyLogic model for the Offering H

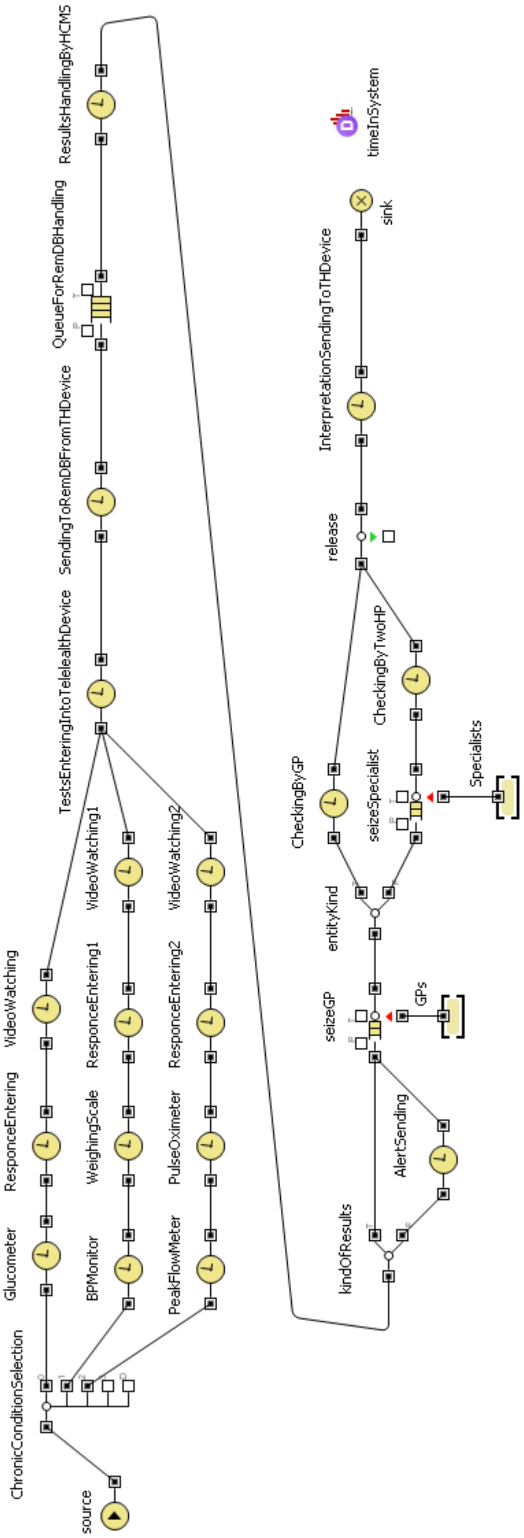

Figure B.9: AnyLogic model for the Offering I

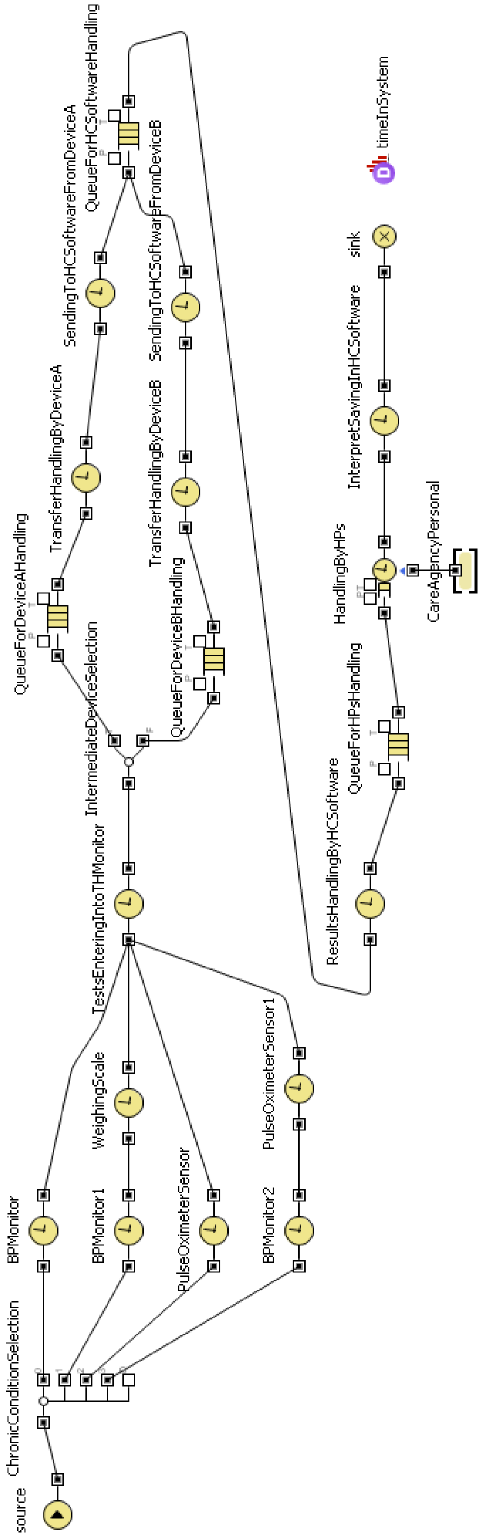

Figure B.10: AnyLogic model for the Offering J

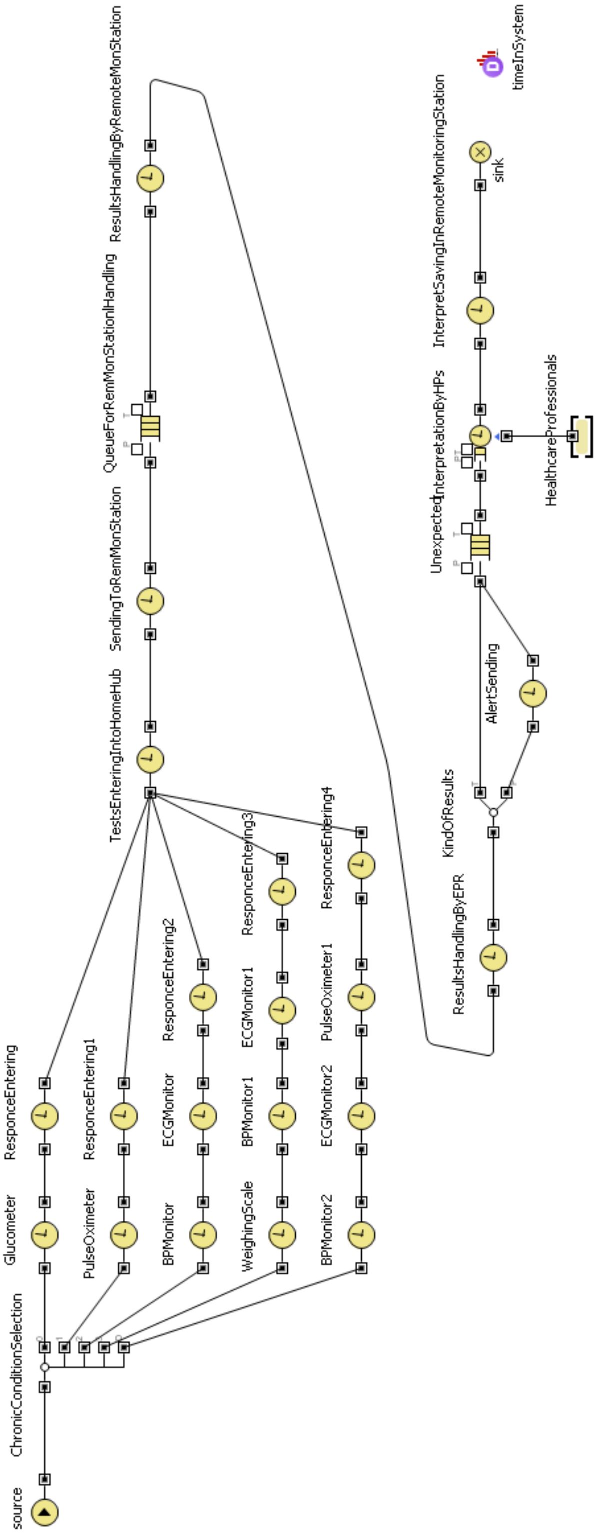

Figure B.11: AnyLogic model for the Offering K

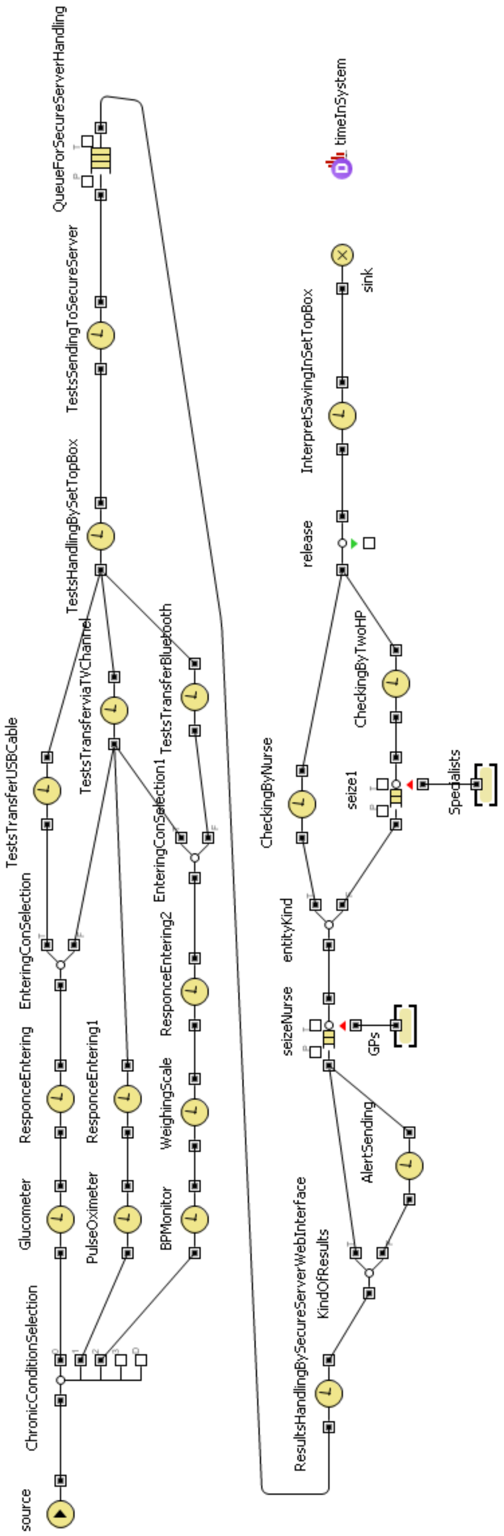

Figure B.12: AnyLogic model for the Offering L