Image Data Flows and Bottlenecks in Medical Informatics: Exploratory Dynamic Simulation of Radiologic Processes at a Moderate-Size California Medical Center

Richard Burkhard
San Jose State University
Thomas Horan
Claremont Graduate University

***Abstract*- The objective of medical informatic systems is to enhance the efficiency of the medical process, especially as it relates to patient interaction with the health care system. This study uses a dynamic simulation model to estimate the current performance of a moderate-size radiological unit in an urban health care center. The principal findings of this case study include description of existing informatics processes, as well as calculated results from dynamic statistical simulation of the system. Bottlenecks were observed throughout the process, with simulation-estimated maximum queues ranging from 33.9 hours (fluoroscopy) to 254.3 hours (general x-rays). The impact of digital systems (e.g. PACS) on each delay point is also discussed. This study demonstrates that the dynamic modeling approach such as by the ARENA model can answer specific questions pertaining to streamlining of complex, multistage medical information processes and assist in cost/benefit analysis for implementation of all-digital alternatives to existing systems.**

I. Introduction

A central objective of medical informatic systems is to enhance the efficiency of the medical process, especially as it relates to patient interaction with the health care system. Over the last decade, a number of systems have been developed to manage healthcare enterprises [1]. In particular, Picture Archiving and Communication Systems (PACS) represent an integrated solution for image-centric operations, such as radiology [2]. Yet, for many small-scale hospitals, PACS systems are viewed as too elaborate to justify the significant initial cost-expenditures. However, there is also the cost (e.g. inefficiency) of current business processes for performing radiology-based examinations. This study uses a dynamic simulation model to estimate the current performance and bottleneck of a moderate-scale radiological unit in an urban medical center. It also discusses the potential impact that a digital infrastructure such as PACS may have on work process and the value of dynamic simulation modeling in assessing these gains.

II. Objectives and Setting

MedCenter, Inc.[1], currently operated by a large national hospital chain, has operated in a major California urban center for more than a century. The facility has over 500 patient beds and employs the services of over 600 affiliated physicians. It is a major teaching hospital for its California region, and is situated close to several other major hospitals, including private hospitals and hospitals operated by municipal, State and Federal Agencies. MedCenter is the official healthcare provider for the one of the region's major sports teams, and possesses a leading spine surgery facility. The radiology department of MedCenter is the primary radiology service provider for three private hospitals in the immediate region.

This study is a preliminary and exploratory investigation of the data and image flows in and around the radiology department of MedCenter. MedCenter makes an especially interesting subject for data and image flow analysis because it is simultaneously a leading radiology facility and an organization that is burdened with complex, problematic and delay-ridden data flows. It makes an excellent subject for the development of a prototype medical data flow simulator. The working hypothesis is that dynamic simulation may offer special insights into the complex interactions and data flows within and around a modern radiology department.

The purpose of this project can be summarized in terms of three, exploratory objectives: Our first objective was to better understand data flows through a modern urban radiology center. Our second objective was to explore the system by developing a prototype data flow simulator. Our third objective was to derive empirical estimates of bottlenecks using this simulator and consider the possible impact of digital systems on these bottlenecks.

A. Radiology Data Flow Process and Potential Bottlenecks

The radiological process has been described by Greenes [3] as having several interweaving steps. Within the context of MedCenter radiology department, these flow patterns for data

[1] MedCenter, Inc. is a pseudonym.

and images at MedCenter radiology department have several dimensions of complexity, which include:

- *Complex, multistage image and document flows.* Images and documents must often be sent to a sequence of several specialists, both on-site and at remote sites around the nation.
- *Multimode data – film and digital images.* Film images must be physically transported (often by overnight delivery services) and are not generally available in digital format. Some equipment does produce digital data, which can theoretically be transported over a high-speed line, but often is stored on a physical medium (e.g., CD-ROM) and transported by courier.
- *Medium to very high data content digital images, with associated need for bandwidth.* MRI and Digital Subtraction Angiography files can be 100MB or larger. High-bandwidth services are required to transmit these data.
- *The frequent need for several specialists to review and append comments to data.* MedCenter specialists must read, diagnose, and extensively comment on images, all of which becomes part of the medical record.
- *Variable number of steps (nodes) in the data path .* Many specialists may be involved from local and remote facilities.
- *Variable review times at each node in the data path.* Each consulting physician will attend to the data or images according to her schedule, and the cumulative delay for these reviews can adversely affect the outcome for the patient.

III. Methodology

This exploratory study had two basic methods.

- Review of case study context through interviews and process review
- Dynamic Simulation through use of ARENA modeling software.

The first method was essential to obtaining the data and perspective on St Mary's in order to conduct the simulation, as well as obtain some perspective on the current process and challenges thereof. A senior staff radiology technologist served as a conduit for obtaining information about the Radiology Department processes, though supplemental information was obtained through contacts with other parts of the radiology unit. Interviews and data-acquisition occurred in October and November 2002.[2]

The second method involved using this data to perform a dynamic simulation modeling using ARENA. ARENA is a process simulation tool used to simulate a variety of business and technological processes, [4], [5], [6]. Process simulation tools such as Arena have gained prominence in the disciplines of operations research and manufacturing process optimization. This study extends the Arena simulation tool to analysis of an applied medical informatics setting.

The ARENA simulation was performed in December 2002 using the inputs and processes outlined below. The system was broken into two sections, and a total of fifty-five processes were required to simulate the various physician reviews, image generation, image distribution and entity control functions. The rate of simulation execution was adjusted to allow visual confirmation of the image entity flows, which are seen as animated components in the model.

IV. Findings

The findings of this case study include both the discovery of the MedCenter Radiology system characteristics and the calculated results of the simulation. These findings are discussed in three sections. First, the discovered entities and processes of the MedCenter system are described, including the fundamental attributes of these entities and processes that are modeled in the simulation. Next, a typical data flow process is described, which formed the basis of the simulation structure. Finally, calculated results of the simulation are discussed.

A. Discovered Entities and Processes

System Entities. The finding entities of interest to this study are the patient records and images created by the system. These entities are created according to exponential or uniform distributions as indicated by best estimates acquired in interviews. In addition, several disposal and accumulator functions are included for management assessment of overall throughput of the system, as well as for transfer of entities between stages of the simulation. For modeling and analysis purposes, the study focused on artifacts created through the following services.

- *General X-ray* services are very common. This service generates x-ray images of all types, and is used in approximately 25% of all clinical events handled by the radiology department. These services generate physical films, which must be developed and physically distributed, either within the hospital facility or to consulting physician's offices.
- *Mammography* services are very common. Mammography is a specialized x-ray technique designed for imaging breast tissue. It generates x-ray films in most cases, and is employed in about 15% of all clinical events handled by radiology. The mammograms must be developed and physically distributed, either within the hospital facility or to consulting physician's offices
- *Magnetic Resonance Imaging (MRI)* is common. Magnetic resonance imaging spectroscopy is an advanced technique that offers image "slices" of the body. It generates digital files of 100 MB or more in size, depending on the number of images, which

[2] Interviews were conducted with a senior department staff member, who in turn obtained the necessary information from other expert sources within the institution.

number from 40-60 or more. MRI is used in about 15% of clinical events handled by the radiology department. This service generates digital images which could theoretically be transported via networks, but are more commonly transferred by physical means.

- *Computed Tomography* is common. CT is a digital system that includes an x-ray source and digital detector. It can be used for many applications and is used in about 15% of all events handled by the radiology department. These services generate physical films, which must be developed and physically distributed, either within the hospital facility or to consulting physician's offices.
- *Sonography* is fairly common. It is used in about 15% of all events that are handled by the radiology department. This technique generates images based on reflection of sound. It generates large data files that, at MedCenter are typically only stored for a period of three days. These large digital records can be copied and distributed under special circumstances.
- *Digital Subtraction* Angiography is fairly common. This technique is used for vascular and heart intervention activities. It generates digital images of 50-100 MB, which must be stored and transferred, and is employed in about 10% of all clinical events handled by the department. The digital images could theoretically be transported over networks, but are more commonly transferred by physical media and means
- *Fluoroscopy* services are comparatively rare. This low-power x-ray technique allows real-time visualization of such invasive procedures as probe insertion and gastro-intestinal series, and is used in about 5% of clinical events handled by the radiology department. X-ray still images are generated by this technique. Fluoroscopy requires extensive physician interaction during the procedure, which results in significant system delay.

Processes. The simulated processes of interest to this study are discussed below. Processing distributions were generally restricted to triangular approximations to normal or other forms, and uniform distributions of various scales. Physician consultations were of two general types.

1) An average of four primary radiologists are on site on a given day. Each of these physicians will temporarily seize data files of all types, and have a generally short queue. Processing distributions were based on best estimates gathered in interviews.

2) Consulting radiologists, whose services are used after a series of images are generated, are estimated to average twelve in number. Processing distributions were based on best estimates gathered in interviews. Processing distributions could be quite extended for these functions and were based on best estimates gathered in interviews.

As noted above (under entities) imaging systems generate data files of various sizes, including digital images and film images. The imaging system processing times were based on best estimates, and followed either triangular approximations or uniform distributions. Image and document distribution (archiving, retrieval and physical distribution) by the system also presents a significant challenge and delay factor. These processes follow a uniform distribution, scaled to best estimates acquired in interviews. The processes were grouped according to the type of image produced, the imaging technology used and the means of distribution (e.g., general x-ray, mammogram and fluoroscopy are all x-ray techniques that produce films requiring physical distribution; MRI and computed tomography are all-digital systems). Four such services were modeled in the system:

1. X-ray Distribution (includes mammogram distribution)
2. Angiogram Distribution
3. MRI / tomography Distribution
4. Sonogram Distribution

Figure 1 provides an overview of the general model structure for these four services, including 1) image creation and distribution, 2) consulting radiological review, and 3) image storage and retrieval.

B. *Typical Data Flow Methods*

One example of an information flow process within the internal and external entities of the Radiology Department involves the generation and processing of medical reports that precede and follow the radiological image. The following process for generation and distribution of the medical commentary and analysis for images for a patient with a back injury who enters the emergency room can illustrate the complexity of this process:

1) General signs and symptoms are manually recorded (handwritten) on a receiving form by the ER physician.

2) Both the ER physician and any other required medical specialist on duty dictate a detailed report on the symptoms and preliminary diagnosis.

3) The preliminary report will be recorded in one of two ways:
   - A transcriptionist listens to the report and generates a document that summarizes the content of the report
   - The physician records the report in digital audio form into a commentary database on a central server.

4) Images are taken as ordered by physicians on duty, according to the availability of equipment and staff.

5) Images are made available to the consulting radiologist by several means:
   - Images can be viewed on-site in film form, or under various circumstances, in digital

form (see simulation for more detailed explanation).
    - Images can be remotely viewed at the radiologist's home or remote office. If available, these versions of the images are typically low-resolution, small file-size renderings of original image. (Many radiologists require this method, and many refuse to utilize this method, for various reasons).

6) A consulting radiologist, who consults at a later time and possibly from a remote location, examines the images and attempts to access the preliminary report in one of several ways:
    - The consulting radiologist can download the transcribed document that contains the text of the preliminary report.
    - The consulting radiologist can call into the server containing the audio commentary and listen to the audio recording of the commentary.

7) The consulting radiologist examines the images, if available, and also generates a detailed report, which may also be generated by transcriptionist or digital audio recording, as available.

8) The radiologist's report is sometimes physically transferred to the primary and consulting physicians for the patient (for example, an internist and a neurologist).

9) The cycle may be repeated for additional images as required by any of the physicians involved.

Figure 2 provides a modeling version of this data flow. While the modeling results are presented below, the perceptions from MedCenter suggest that the complexity of these data flows leads to many complications and delays. The opinion of those providing information about the MedCenter radiology department is that the systems is inefficient in many ways: Images and data are often greatly delayed and sometimes misplaced or lost . Consulting physicians often do not know patient ID codes and cannot proceed with analysis or diagnosis. Large images are sometimes only stored for three days and then expunged (because there is no long-term storage for some types of files). Physicians often cannot understand digital audio transcripts. Finally, patient records are sometimes misplaced

Despite these expressed frustrations, the Picture Archiving and Communications System (PACS), which has been adopted by approximately 20% of such facilities nationwide, is not used at MedCenter. The all-digital PACS system allows theoretically rapid access to images for any consulting physician, and would greatly reduce problems in data flows. The high cost of the PACS system has prevented many hospitals from acquiring the technology. The ARENA simulation aims to provide information of the "cost of the default alternative" in terms of delay.

C. Simulation Results

The simulation model successfully captured many of the major elements in the Radiology Department data and image flow network. The final version of the model contained fifty-five processes and entity controllers, as well as several counters with graphic display. The model was segmented into two parts. Figures 1 and 2 show the process and counter elements of both sections of the model, and Figures 3 and 4 illustrate animation during simulation execution. Iterative execution of the model revealed insignificant variation in outcomes.

As expected, cumulative delay from sequential processes leads to significant end-to-end delay in patient service delivery (see Table 1). The specific elements of delay include two radiology consultations, image service queues, as well as archiving and distribution, which is the major non-physician delay in the system. Queuing for each of these functions, as well as the inherent delay that stems from physical transfer of images, is a significant problem and inefficiency of the system. The existing simulations show the following examples for queuing functions for several processes:

- *Impact of traditional (non-digital) distribution on x-ray based imagery services.* The computed tomography queue averaged 29.5 hours, and had a maximum value of 58.4 hours. The fluoroscopy queue averaged 33.9 hours, with a maximum value of 60.1 hours. The general x-ray queue averaged 28.7 hours, and could be as high as 62.7 hours. However, the archiving and distribution of these images added significant delay to these base figures. For example, the mean distribution time for x-rays was approximately 80.6 hours, with a maximum of 254.3 hours. In other words, simply archiving, pulling and distributing x-ray images to various consulting physicians can introduce a delay of three to ten days (this does not include misplaced files, which occasionally happens). This is a prime opportunity for introduction of potential improvements by a networked digital distribution system (such as PACS).
- *Impact of traditional (non-digital) distribution on MRI imagery services:* The MRI queue averaged 41.1 hours, with a minimum of 1.2 hours and a maximum value of 60.8 hours. Distribution times for these images ranges from immediate to as long as 12 days. Such distribution could also be accomplished over secure, high-bandwidth networks, which would reduce the distribution to a very small period of time.
- *Impact of traditional (non-digital) distribution on angiography imagery services.* The digital subtraction angiography queue ranged from 24.1 to 58.4 hours. Distribution of these images average 74.6 hours, or about three days.
- Impact of traditional (non-digital) distribution on fluoroscopy and sonography imagery services. *The fluoroscopy queue ranged from 0.4 hours to 60.9 hours. Image distribution added an average of three*

days to this process. While the sonography queue averaged 25.7 hours, the comparatively rare distribution of these images can range up to several days. In both cases, digital archiving and distribution over high-bandwidth networks could greatly reduce the end-to-end processing time.

TABLE I
SIMULATED DELAY TIMES FOR RADIOLOGIC SERVICES

Process	Minimum delay (hrs)	Maximum delay	Mean delay
General X-Ray Imaging	0.51	62.78	28.7
MRI Imaging	1.21	60.87	41.12
X-Ray distribution	0.00	254.31	80.60
Digital Angiogram distribution	0.00	265.62	74.41

V. CONCLUSION

Dynamic simulation allows modeling of complex systems, such as medical imaging in radiology services, in ways that static models cannot capture. Traditional applications of dynamic process simulation are seen in operations research, and have many practical applications in manufacturing process analysis. Information technology has seen several specialized simulation programs for network modeling, such as OPNET (Martinez, et al, 1998).

The dynamic simulation technique used in this study appears to be well suited to analyses of medical data and image generation and distribution. There is much promise for use of this technique for analysis of complex, multi-stage, multi-process data flow systems such as those seen in a radiology department. This project confirms the potential of this technique for data flow simulation in a medical informatics environment, and as such it is a proof of concept.

The principal finding of this case study is that the this modeling technique can be used to answer specific questions pertaining to streamlining alternatives and cost/benefit analysis for implementation of all-digital alternatives to existing systems. The potential time savings of a system such as PACS can be clearly demonstrated in a real medical environment.

With adequate refinement and validation within the work environment, this technique can capably identify major bottlenecks in a medical image processing and distribution network. The next step would be to (re)calibrate these simulated findings with empirical performance data and then estimate bottleneck improvements from digital (e.g. PACS) implementations. On a more general level, additional ARENA-based simulations involving complex, multistage medical information environments should be considered for modeling in this manner.

REFERENCES

[1] Yukio Kurihara, Y. Okuhara, Y., Narita, Y., Kitazoe, Y., Sawada, A., Yoshida, S., Integration of Medical Images into the Total Hospital Information System - Experiences at Kochi Medical School, Proceedings of the 32nd Hawaii International Conference on System Science, 1999

[2] Huang, PACS: Basic Principles and Applications, New York: John Wiley, 1999.

[3] Greenes, RA and Brinkley, J. Imaging Systems, in E.H. Shortliff, L.E. Perreault, G. Wiederhold, and L.M. Fagan (EDS), Medical Informatics: Computer Applications in Health Care and Biomedicin,e New York: Springer Verlag, 2000.

[4] Kelton, W.D., R.P. Sadowski, and D.A. Sadowski, Simulation with Arena; Second edition. WCB/McGraw-Hill, Boston, 2002

[5] Martinez, R., Bradford, D., Hatch, J., Sochan, J., Chimiak, W., "Modeling and Simulation of the USAVRE Network and Radiology Operations", Proceedings of the SPIE Medical Imaging Conference, San Diego, CA, February 1998

[6] Venkateswaran, Jafferali, M., Son, Y, Distributed simulation: an enabling technology for the evaluation of virtual enterprises. Winter Simulation Conference, 856-862, 2001.

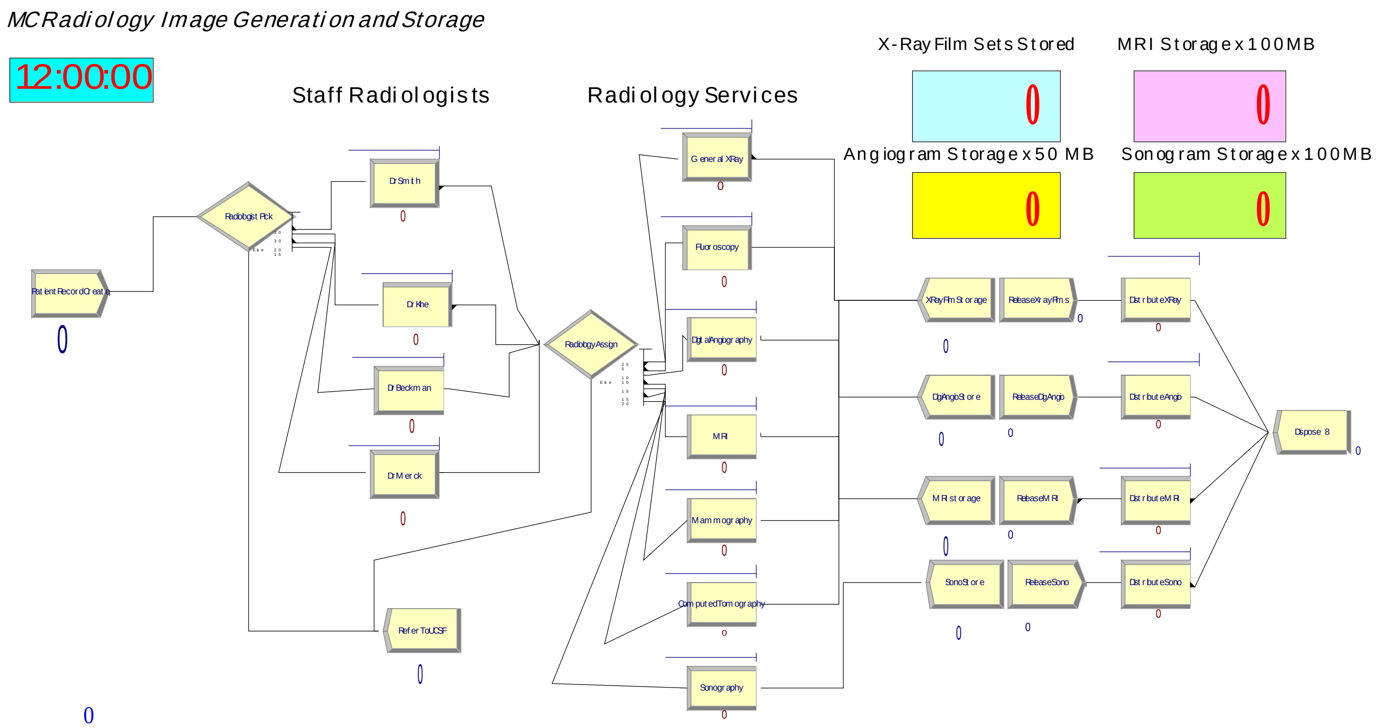

Figure 1: Simulation Model, Part One

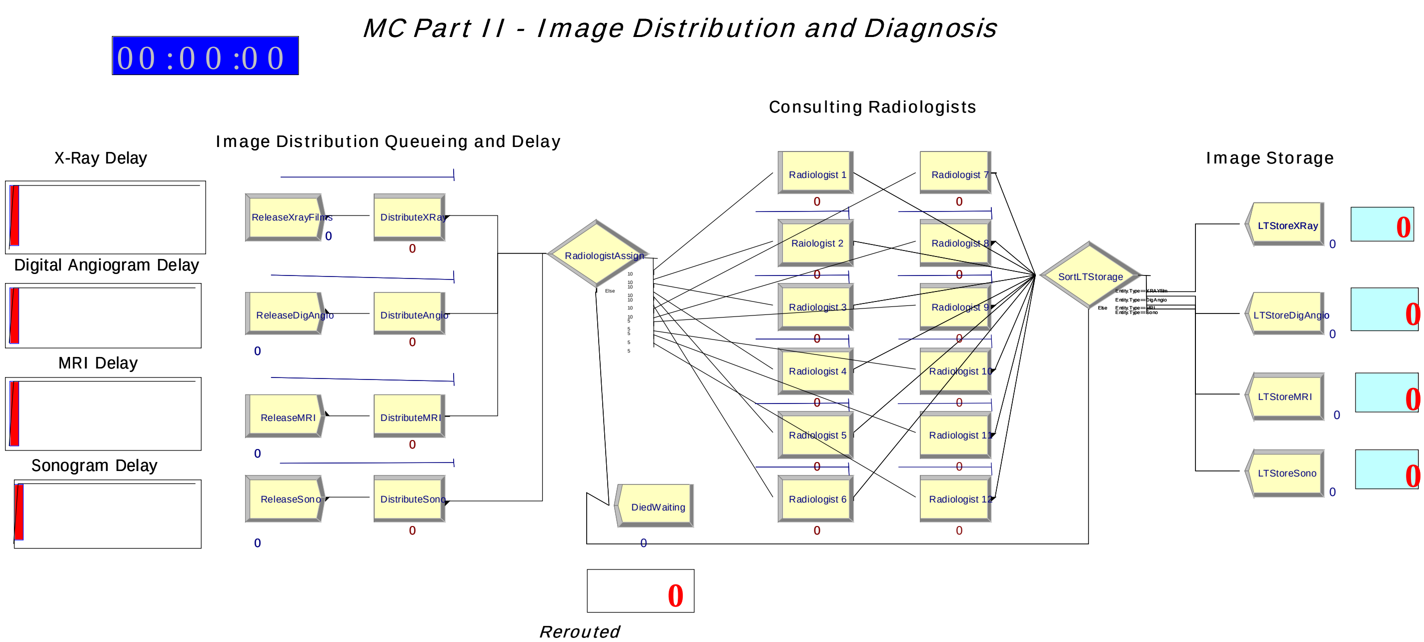

Figure 2: Simulation Model, Part Two